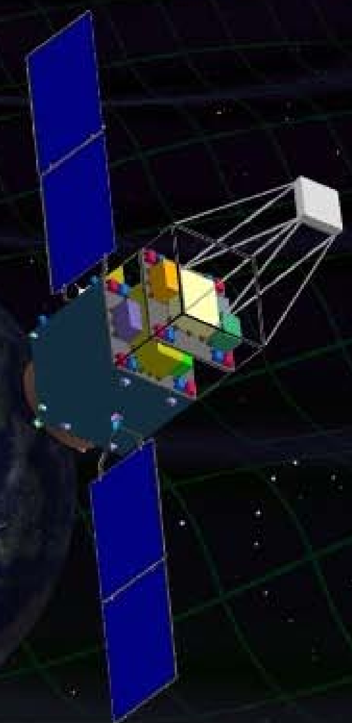
DECIGO

the Japanese Space Gravitational Wave Antenna

Original
Picture : Sora

Masaki Ando

(Department of Physics, Kyoto University)



Seiji Kawamura, Takashi Nakamura, Kimio Tsubono, Takahiro Tanaka, Ikkoh Funaki, Naoki Seto, Kenji Numata, Shuichi Sato, Nobuyuki Kanda, Takeshi Takashima, Kunihito Ioka, Kazuhiro Agatsuma, Tomotada Akutsu, Tomomi Akutsu, Koh-suke Aoyanagi, Koji Arai, Yuta Arase, Akito Araya, Hideki Asada, Yoichi Aso, Takeshi Chiba, Toshikazu Ebisuzaki, Motohiro Enoki, Yoshiharu Eriguchi, Masa-Katsu Fujimoto, Ryuichi Fujita, Mitsuhiro Fukushima, Toshifumi Futamase, Katsuhiko Ganzu, Tomohiro Harada, Tatsuaki Hashimoto, Kazuhiro Hayama, Wataru Hikida, Yoshiaki Himemoto, Hisashi Hirabayashi, Takashi Hiramatsu, Feng-Lei Hong, Hideyuki Horisawa, Mizuhiko Hosokawa, Kiyotomo Ichiki, Takeshi Ikegami, Kaiki T. Inoue, Koji Ishidoshiro, Hideki Ishihara, Takehiko Ishikawa, Hideharu Ishizaki, Hiroyuki Ito, Yousuke Itoh, Shogo Kamagasako, Nobuki Kawashima, Fumiko Kawazoe, Hiroyuki Kirihara, Naoko Kishimoto, Kenta Kiuchi, Shiho Kobayashi, Kazunori Kohri, Hiroyuki Koizumi, Yasufumi Kojima, Keiko Kokeyama, Wataru Kokuyama, Kei Kotake, Yoshihide Kozai, Hideaki Kudoh, Hiroo Kunimori, Hitoshi Kuninaka, Kazuaki Kuroda, Kei-ichi Maeda, Hideo Matsuhara, Yasushi Mino, Osamu Miyakawa, Shinji Miyoki, Mutsuko Y. Morimoto, Tomoko Morioka, Toshiyuki Morisawa, Shigenori Moriwaki, Shinji Mukohyama, Mitsuru Musha, Shigeo Nagano, Isao Naito, Noriyasu Nakagawa, Kouji Nakamura, Hiroyuki Nakano, Kenichi Nakao, Shinichi Nakasuka, Yoshinori Nakayama, Erina Nishida, Kazutaka Nishiyama, Atsushi Nishizawa, Yoshito Niwa, Masatake Ohashi, Naoko Ohishi, Masashi Ohkawa, Akira Okutomi, Kouji Onozato, Kenichi Oohara, Norichika Sago, Motoyuki Saijo, Masaaki Sakagami, Shin-ichiro Sakai, Shihori Sakata, Misao Sasaki, Takashi Sato, Masaru Shibata, Hisaaki Shinkai, Kentaro Somiya, Hajime Sotani, Naoshi Sugiyama, Yudai Suwa, Hideyuki Tagoshi, Kakeru Takahashi, Keitaro Takahashi, Tadayuki Takahashi, Hirotaka Takahashi, Ryuichi Takahashi, Ryutaro Takahashi, Takamori Akiteru, Tadashi Takano, Keisuke Taniguchi, Atsushi Taruya, Hiroyuki Tashiro, Mitsuru Tokuda, Masao Tokunari, Morio Toyoshima, Shinji Tsujikawa, Yoshiki Tsunesada, Ken-ichi Ueda, Masayoshi Utashima, Hiroshi Yamakawa, Kazuhiro Yamamoto, Toshitaka Yamazaki, Jun'ichi Yokoyama, Chul-Moon Yoo, Shijun Yoshida, Taizoh Yoshino

27th International Symposium on Space Technology and Science (July 9, 2009, Tsukuba, Ibaraki)

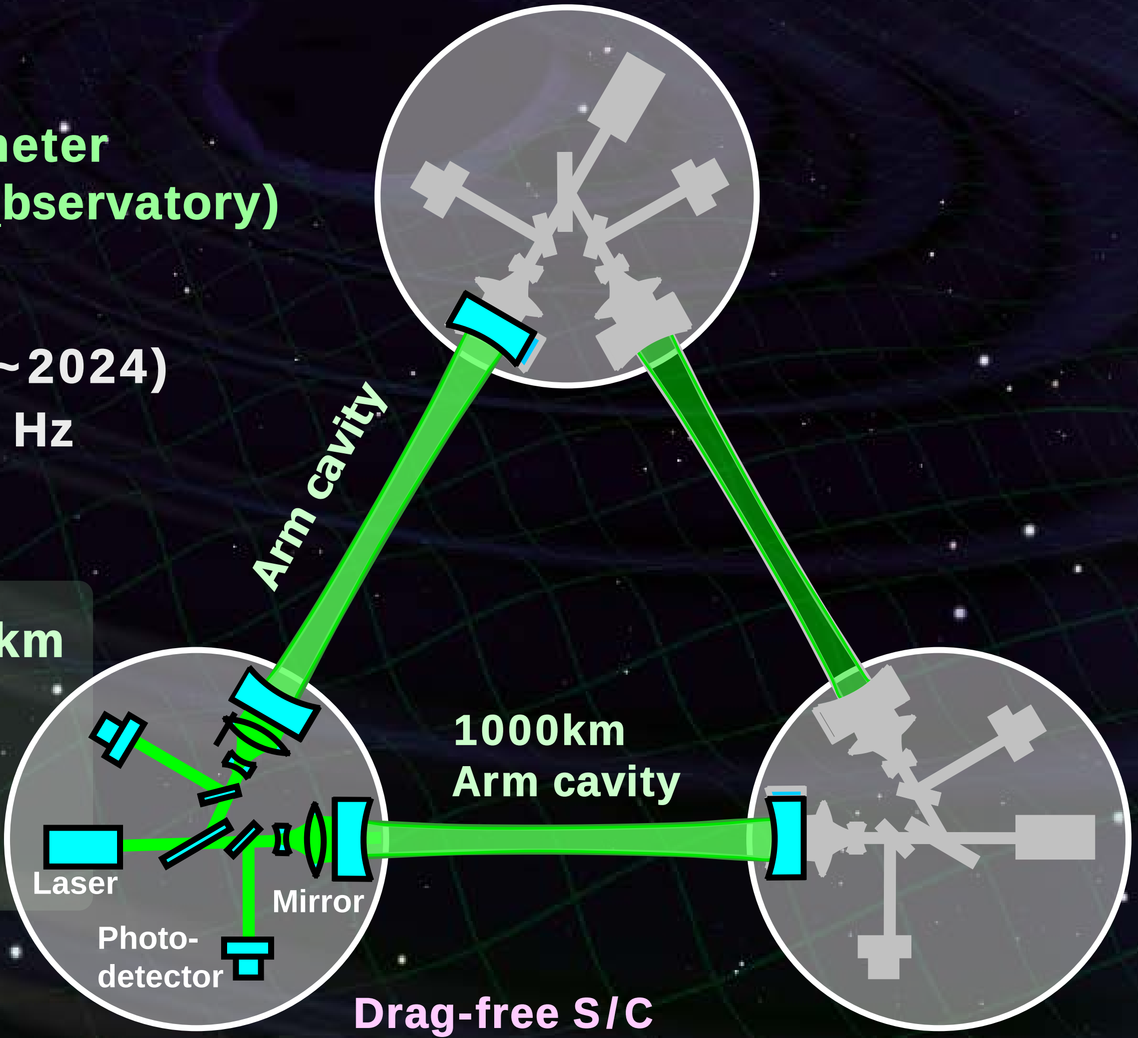
DECIGO

DECIGO

(Deci-hertz interferometer
Gravitational wave Observatory)

Space GW antenna (~2024)
Obs. band around 0.1 Hz

Baseline length: 1000 km
3 S/C formation flight
3 FP interferometers
Drag-free control



1. DECIGO

- GW observation and Science
- Pre-conceptual Design

2. DECIGO Pathfinder

- Overview and Design
- Status

3. Summary

1. DECIGO

GW observation and Science

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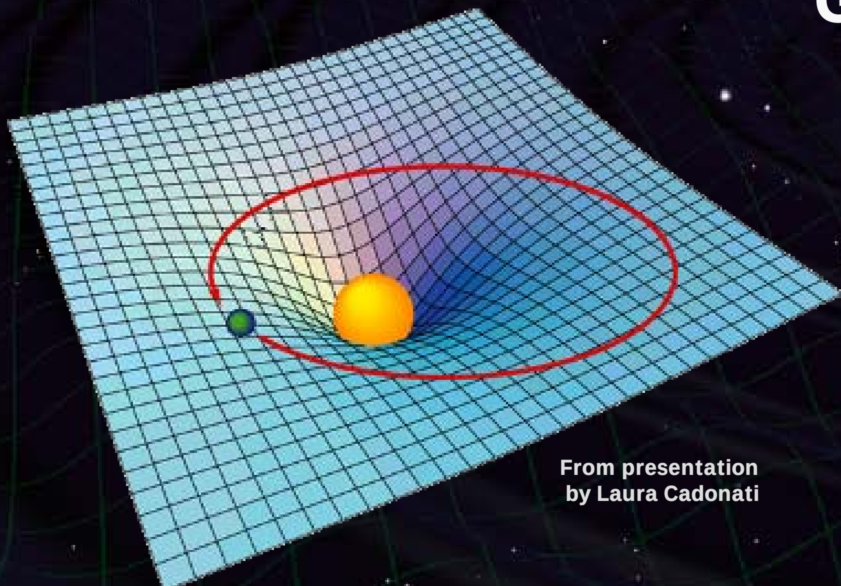
Gravitational Waves

General Relativity

→ Interpret gravity as nature of space-time



From presentation by Laura Cadonati

"Mass tells space-time how to curve, and space-time tells mass how to move. "

John Archibald Wheeler

Einstein equation

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$G_{\mu\nu}$: Curvature of Space-time

$T_{\mu\nu}$: Mass (Energy-Momentum)

Motion of Mass

→ Ripples in gravitational field

→ Propagate as waves

⇨ **Gravitational Waves**

EM and GW waves

Electromagnetic wave
J.C. Maxwell

Waves in electromagnetic field

Solution of the Maxwell equations

1864 : Predicted by Maxwell
1888 : Confirmed by the Hertz's experiment

Radiated by acceleration of charged particles
Utilized in telecommunications and observations

Gravitational wave
A. Einstein

Waves in space-time (gravitational field)

Solution of the Einstein equation

1918: Predicted by Einstein
1989: Confirmed by a Binary pulsar observation

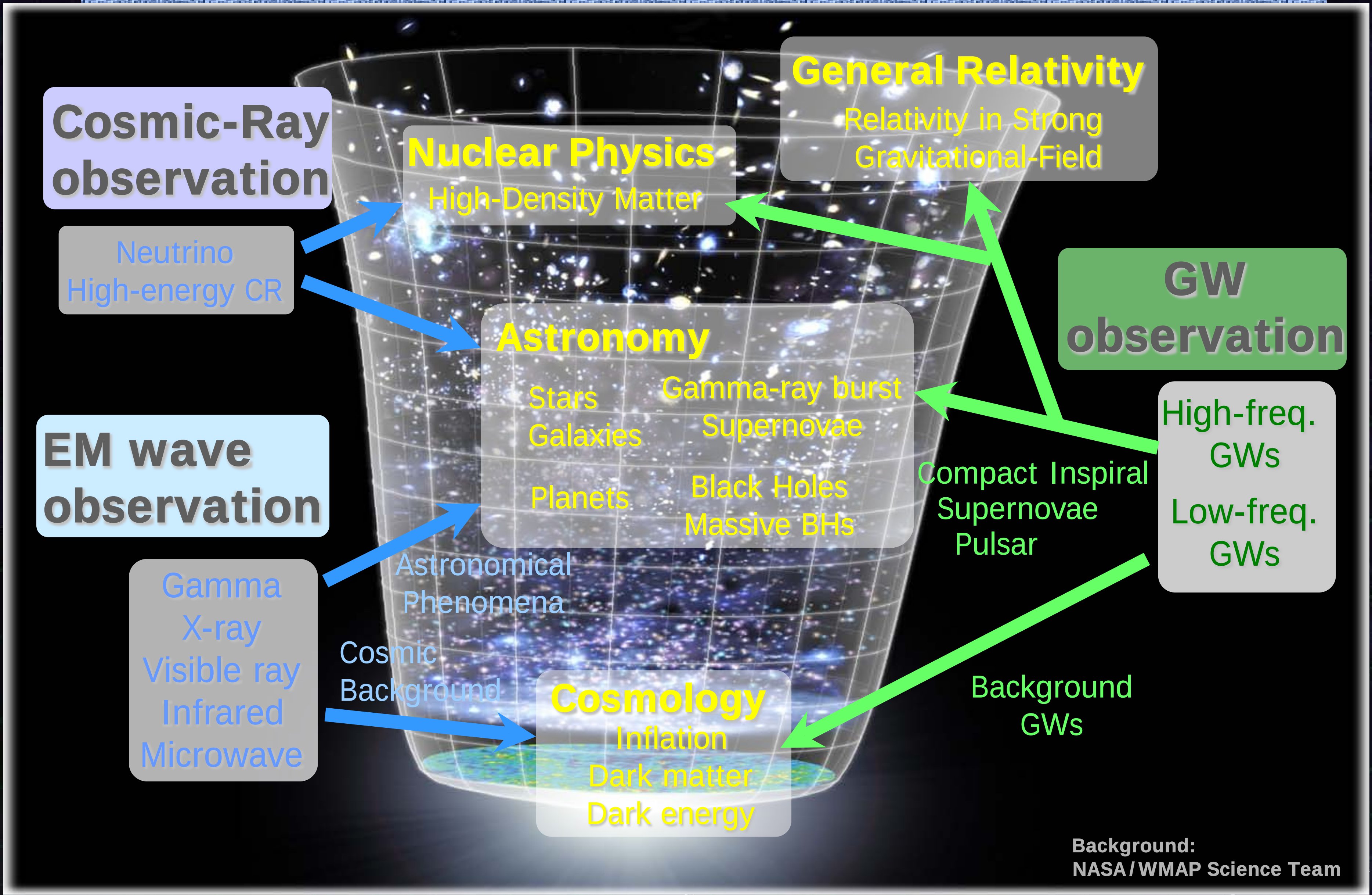
Radiated by acceleration of masses
High transmittance through matter (Small interactions with matter)

'Gravitational-wave astronomy'

Independent Information

- Direct probe of dynamic motion of matters
- Early universe before recombination

Astronomical Probes

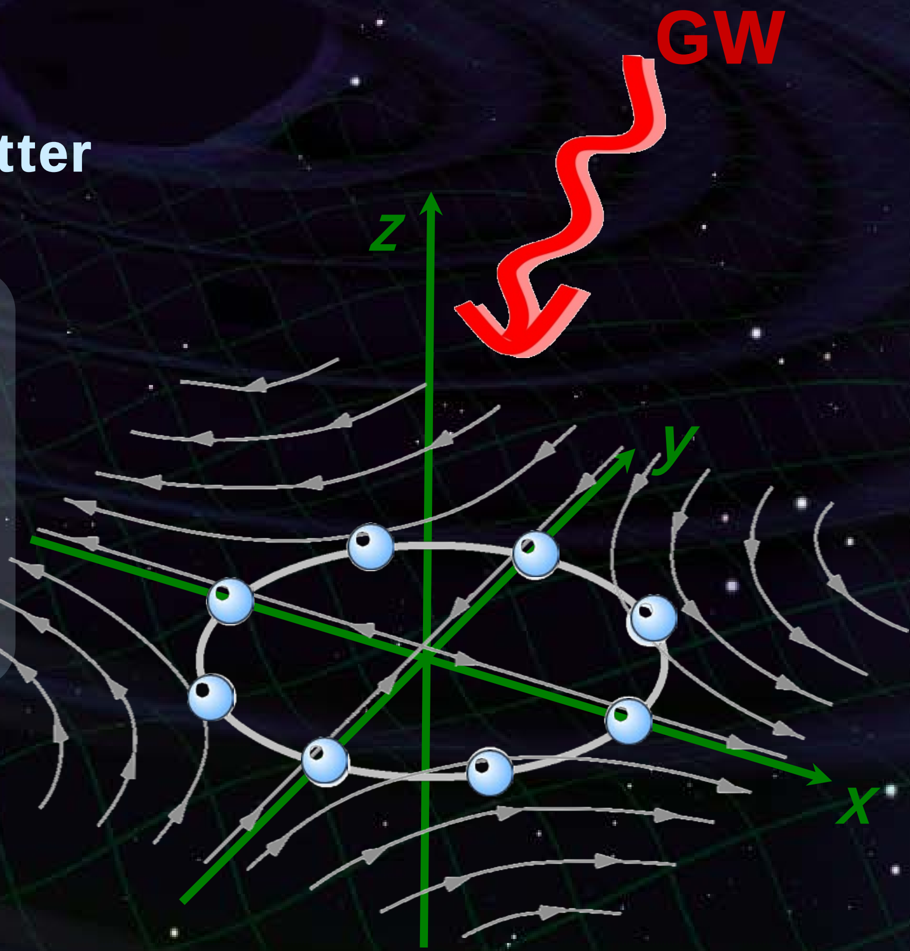


Effect of Gravitational waves

Gravitational Waves

Change in proper distance

Tidal force for finite-sized matter



GW amplitude *h* :

Strain (dimensionless)

Typical amp. $h = 10^{-21}$

→ distance change by 10^{-21}m for 1-m separation

⇩

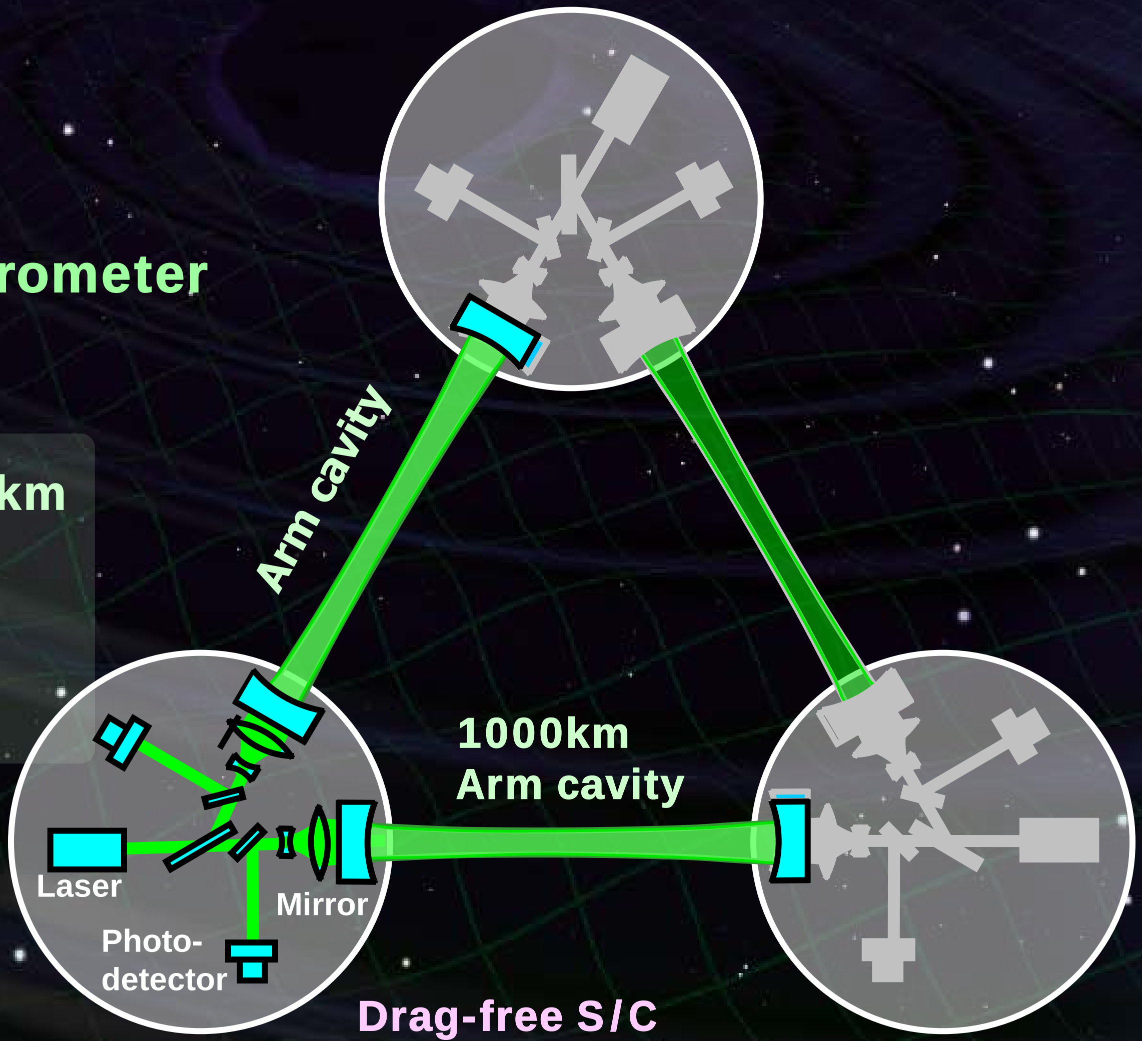
Precise length measurement with long baseline

→ Formation flight mission

DECIGO Interferometer

Interferometer Unit:
Differential FP interferometer

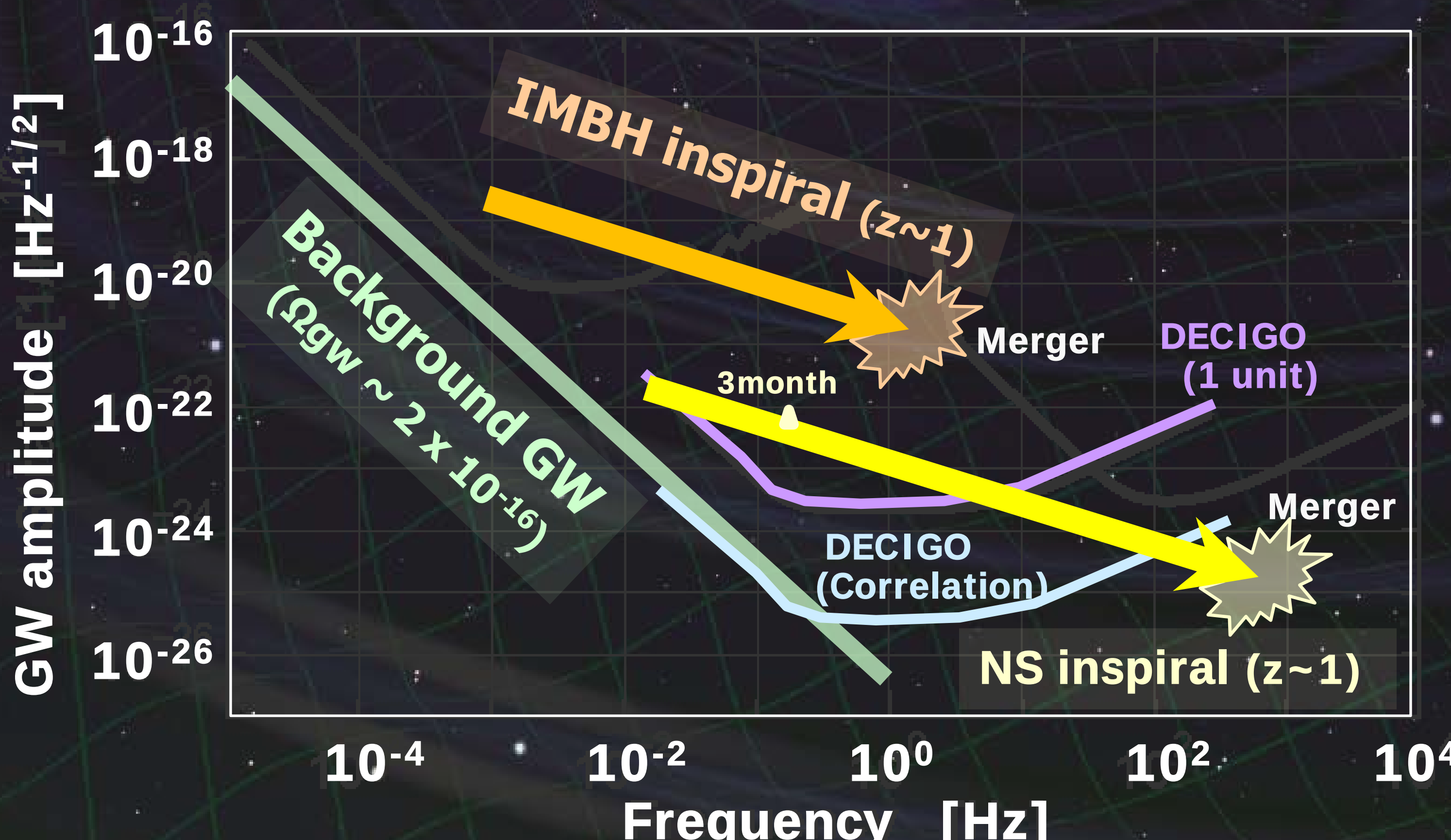
Baseline length: 1000 km
3 S/C formation flight
3 FP interferometers
Drag-free control



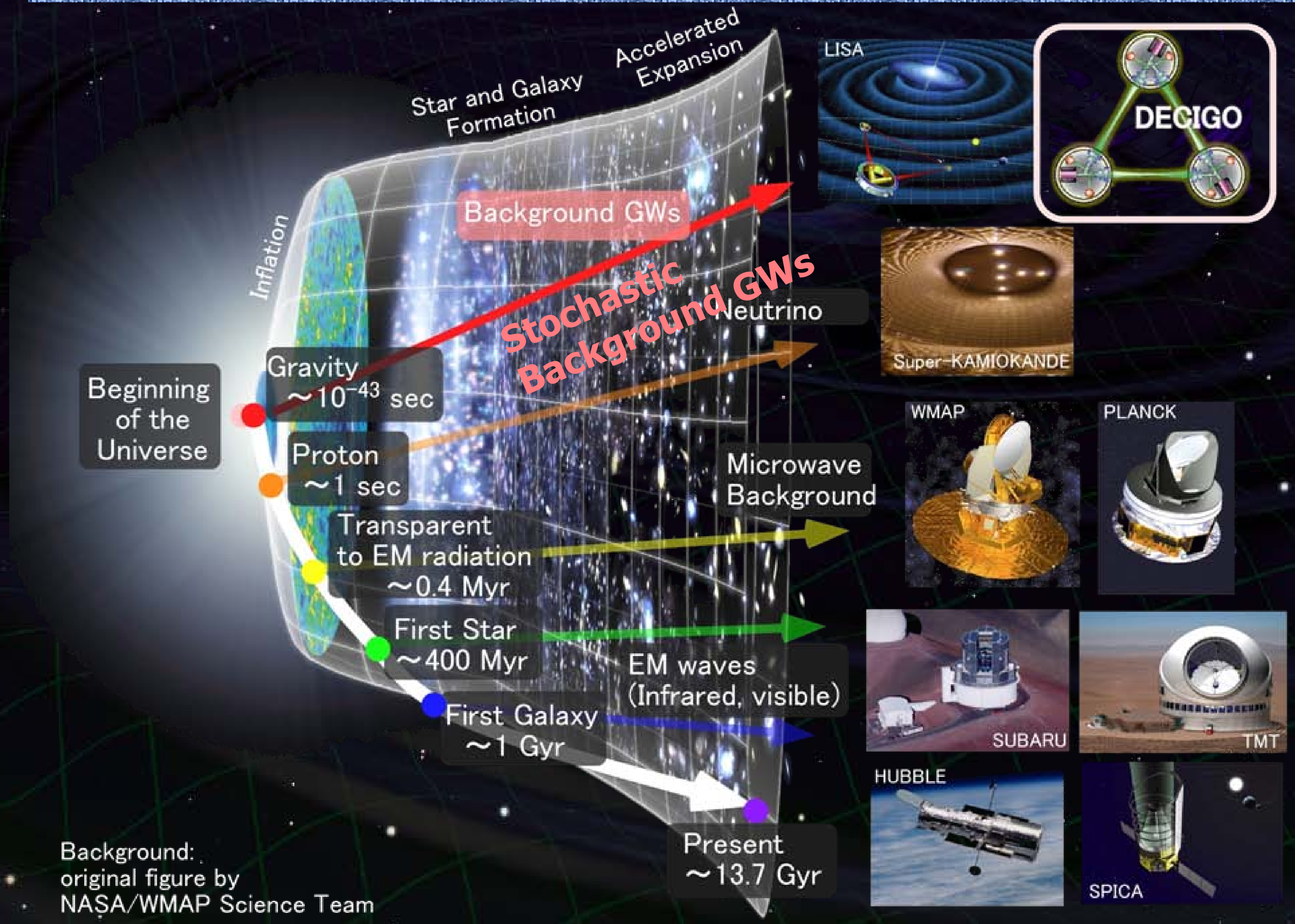
Targets and Science

IMBH binary inspiral
NS binary inspiral
Stochastic background

⇨ Galaxy formation (Massive BH)
Cosmology
(Inflation, Dark energy)



Stochastic Background GWs



1. DECIGO

GW observation and Science

⇨ **Pre-conceptual Design**

2. DECIGO Pathfinder

Overview and Design

Status

3. Summary

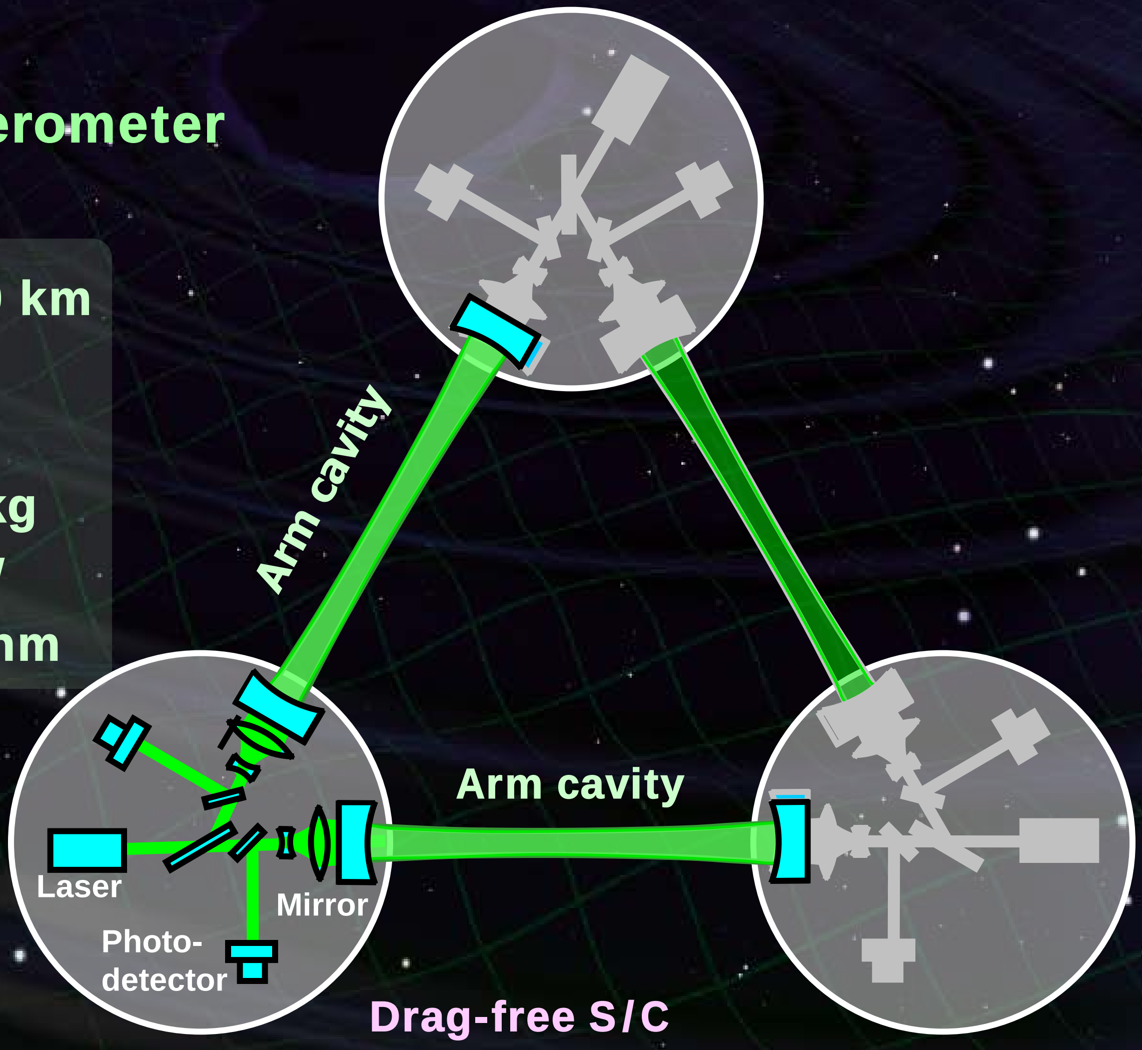
Pre-Conceptual Design

Interferometer Unit:

Differential FP interferometer

Arm length:	1000 km
Finesse:	10
Mirror diameter:	1 m
Mirror mass:	100 kg
Laser power:	10 W
Laser wavelength:	532 nm

S/C: drag free
3 interferometers



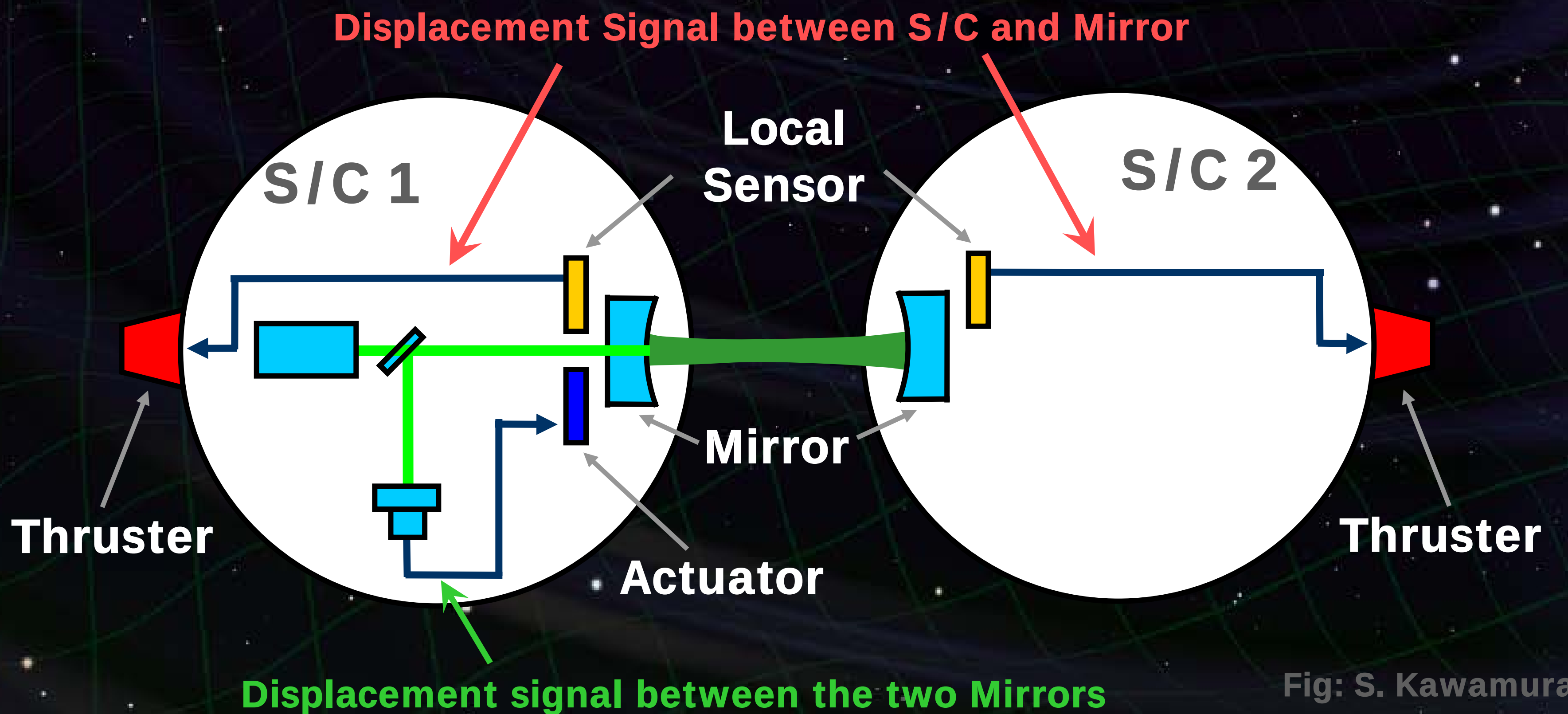
Cavity and S/C control

Cavity length change

PDH error signal → Mirror position (and Laser frequency)

Relative motion between mirror and S/C

Local sensor → S/C thruster



Requirements

Sensor Noise

Shot noise 3×10^{-18} m/Hz$^{1/2}$ (0.1 Hz)

⇨ x 10 of LCGT in phase noise

Other noises should be well below the shot noise

Laser freq. noise: 1 Hz/Hz$^{1/2}$ (1Hz)

Stab. Gain 10^5, CMRR 10^5

Acceleration Noise

Force noise 4×10^{-17} N/Hz$^{1/2}$ (0.1 Hz)

⇨ x 1/50 of LISA

External force sources

Fluctuation of magnetic field, electric field, gravitational field, temperature, pressure, etc.

Thruster

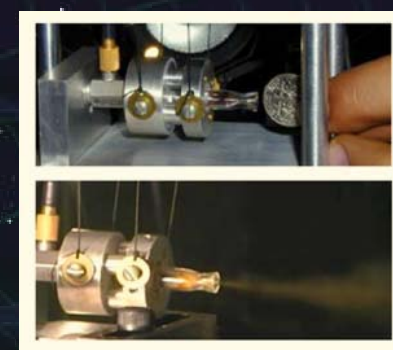
Requirements for thrusters

- Compensate external forces
- Low thrust noise
- Quick response
- Long lifetime

⇨

- Max. thrust 100 μN (variable thrust)
- Thrust noise $\delta F_{thruster} < 10^{-7}$ N/Hz$^{1/2}$
- Response > 10 Hz
- Total impulse > 10^4 Ns

Thruster candidates

	Ion Thruster	FEEP Thruster	Cold Gas Jet
Type	 JPL Miniature Xenon Ion Thruster	 ESA FEEP Thruster Array	
Thrust control	Voltage, Pressure	Bias Voltage	Gas pressure
Response	<500ms ?	<10ms	<100ms0
		0.1μN/Hz$^{1/2}$	500μN/Hz$^{1/2}$
Noise sources	Current, Heat, Discharge	Current, Heat, Discharge	Gas flow, Vulve

Orbit and Constellation

Candidate of orbit:

Record-disk orbit around the Sun

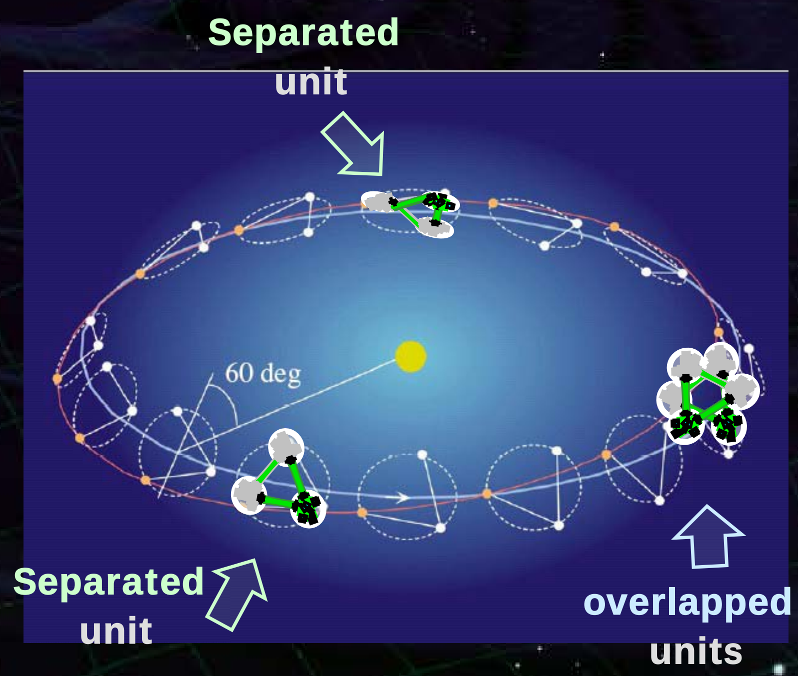
Relative acc. 4×10^{-12} m/s^2

(Mirror force ~10^{-9} N)

Halo orbit around L2 (or L1)

Relative acc. 4×10^{-7} m/s^2

(Mirror force ~10^{-4} N)



Constellation

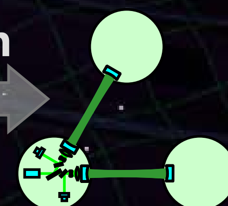
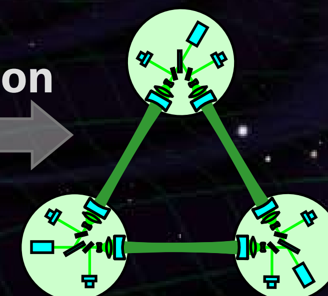
4 interferometer units

2 overlapped units → Cross correlation

2 separated units → Angular resolution

Roadmap

Figure: S.Kawamura

	2007 08 09 10 11 12 13	14 15 16 17 18 19	20 21 22 23 24 25 26
Mission	R&D Fabrication →  SDS-1/SWIM  DECIGO Pathfinder (DPF)	R&D Fabrication →  Pre-DECIGO	R&D Fabrication →  DECIGO
Objective	Space test of key tech. GW observation	Detect GW with min. spec FP between S/C	GW astronomy
Design	Single small satellite Short FP interferometer	3 S/C 1 interferometer unit	3 S/C x 3-4 units

1. DECIGO

GW observation and Science

Pre-conceptual Design

⇨ 2. DECIGO Pathfinder

Overview and Design

Status

3. Summary

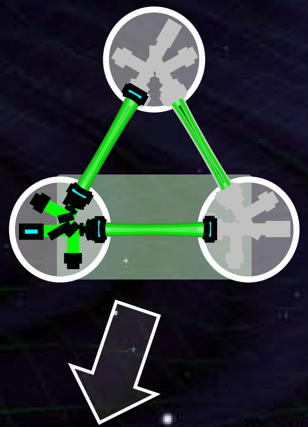
DECIGO-PF

DECIGO Pathfinder (DPF)

First milestone mission for DECIGO

Shrink arm cavity

DECIGO 1000km → DPF 30cm



Single satellite

(Payload ~1m³ , 350kg)

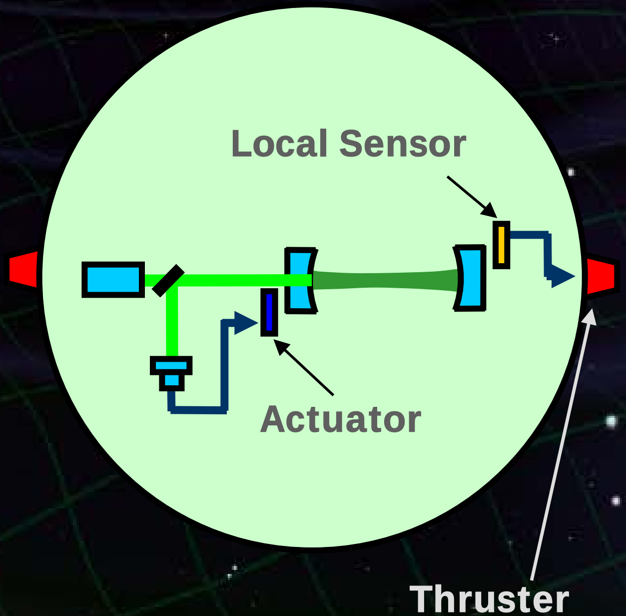
Low-earth orbit

(Altitude 500km, sun synchronous)

30cm FP cavity with 2 test masses

Stabilized laser source

Drag-free control



DPF satellite

DPF Payload

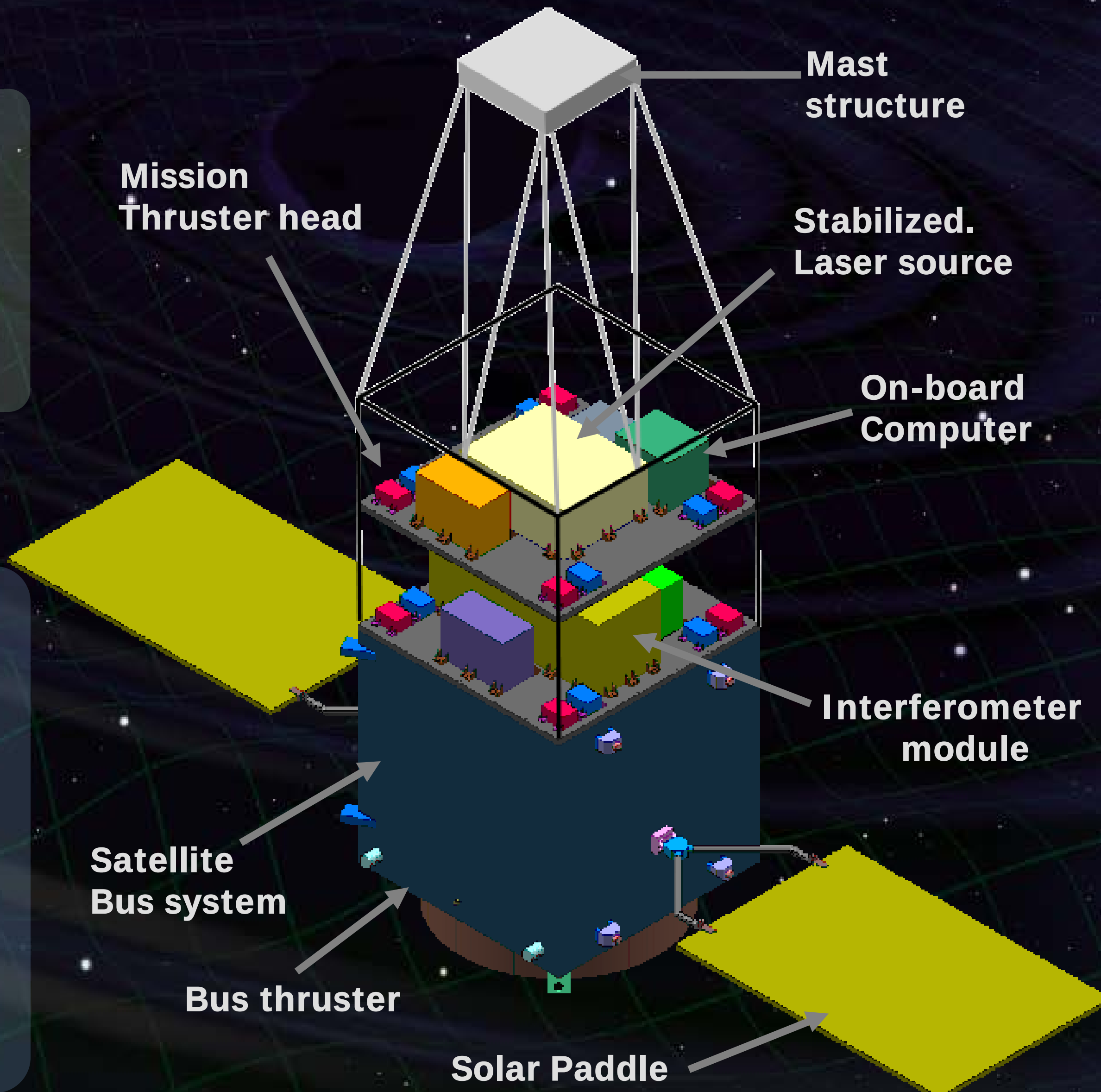
Size : 950mm cube
Weight : 150kg
Power : 130W
Data Rate: 800kbps
Mission thruster x12

Power Supply
SpW Comm.

Satellite Bus

('Standard bus' system)

Size :
950x950x1100mm
Weight : 200kg
SAP : 960W
Battery: 50AH
Downlink : 2Mpbs
DR: 1GByte
3N Thrusters x 4



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R&D for DPF (2)

Attitude control and Drag-free

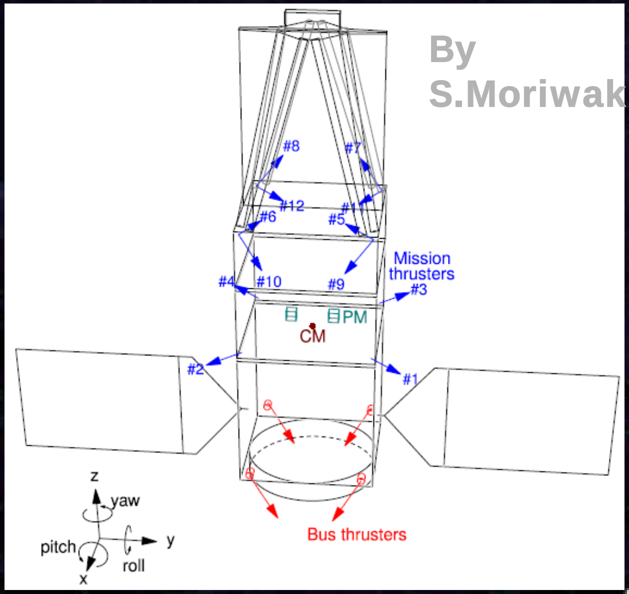
Satellite structure (mass distribution)

Passive attitude stabilization by gravity gradient

Mission thruster position

Control topology

By S.Moriwaki



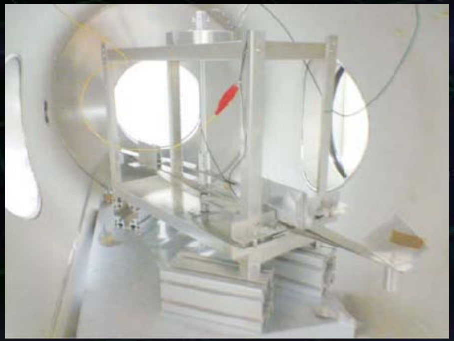
Thruster

System design with existing tech.

Noise meas. system (thruster stand)

Development of Slit FEEP

By I.Funaki



SWIM launch and operation

Tiny GW detector module
Launched in Jan. 23, 2009
⇨ **In-orbit operation**

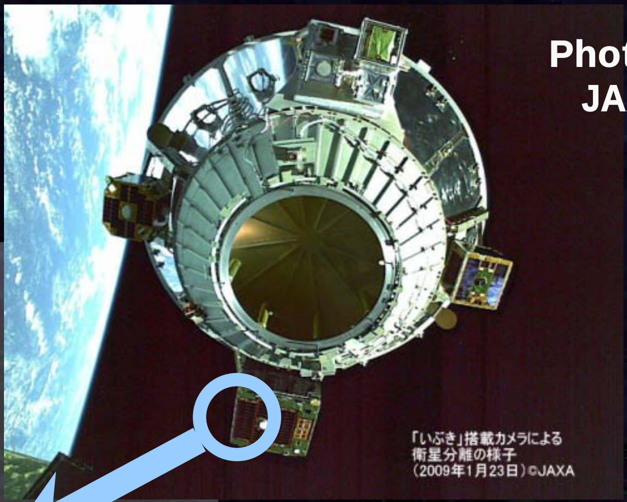


Photo: JAXA

TAM: Torsion Antenna Module with free-falling test mass
(Size : 80mm cube, Weight : ~500g)

Test mass

~47g Aluminum, Surface polished
Small magnets for position control

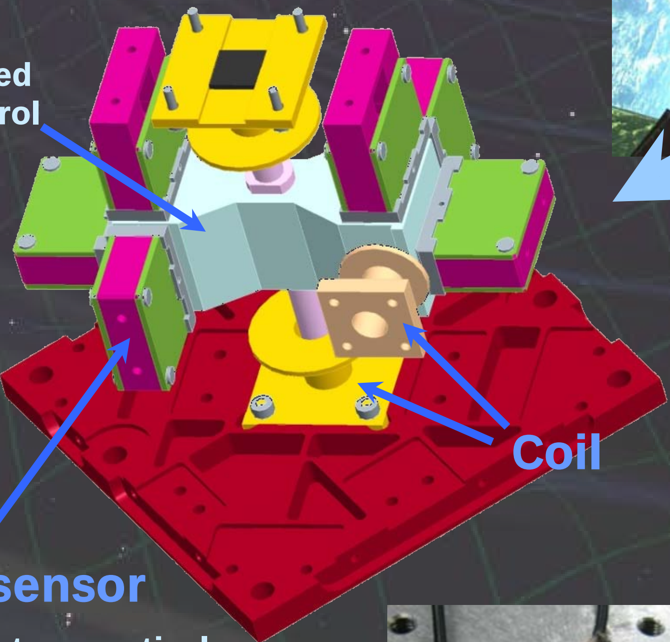
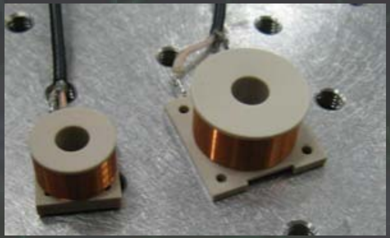


Photo sensor

Reflective-type optical displacement sensor
Separation to mass ~1mm
Sensitivity ~ 10^{-9} m/Hz$^{1/2}$
6 PSs to monitor mass motion



Successful control

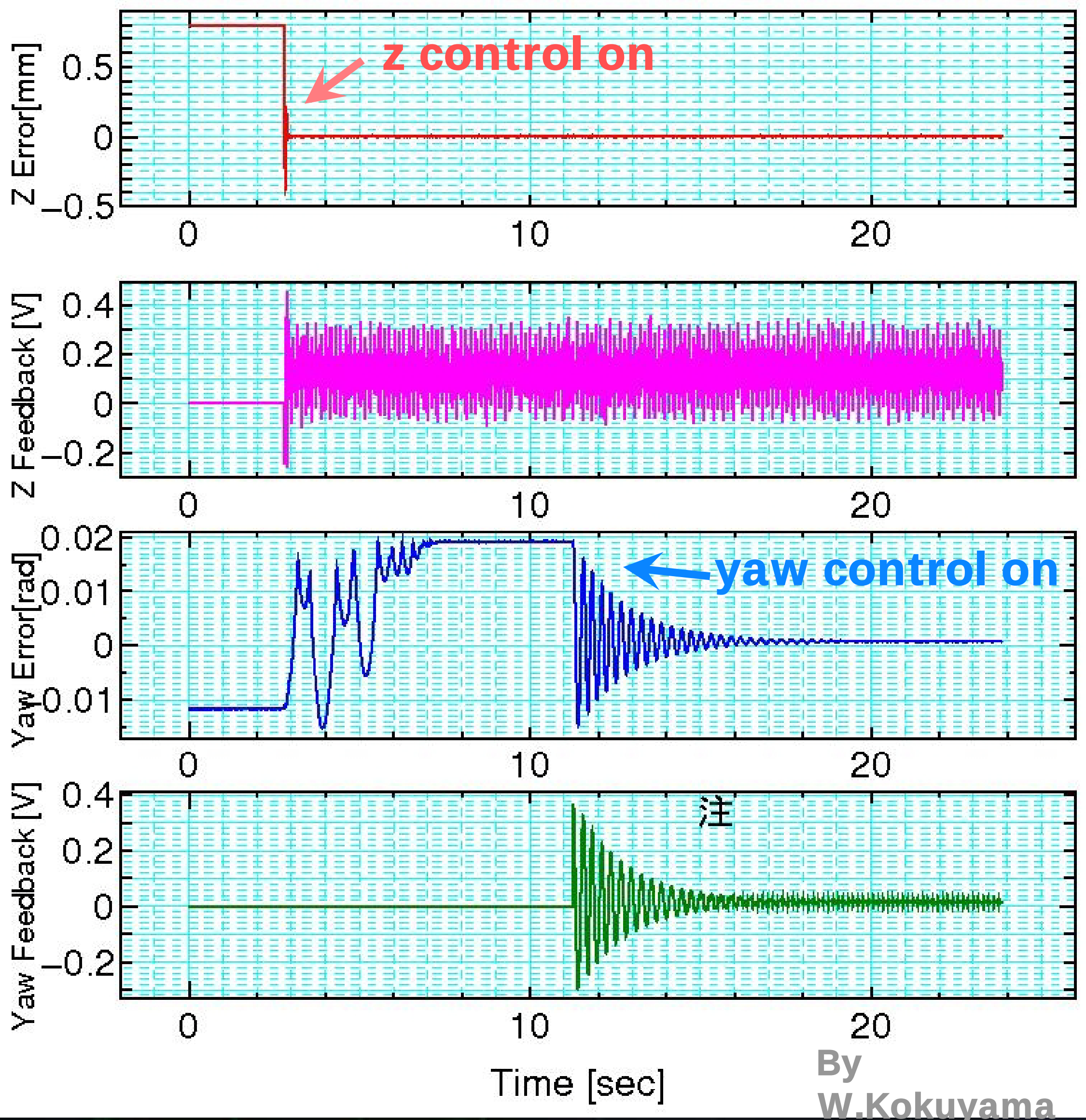
SWIM
In-orbit operation

Test mass controlled

- Error signal → zero
- Damped oscillation (in pitch DoF)
- Free oscillation in x and y DoF
- Signal injection → OL trans. Fn.

Operation: May 12, 2009

Downlink: ~ a week



DPF mission status

DPF : One of the candidate of
JAXA's small satellite series

At least 3 satellite in 5 years with
Standard Bus + M-V follow-on rocket

SPRINT-A /EXCEED

1st mission (2012): SPRINT-A/EXCEED
2nd mission (~2013) in selection

DPF is one of candidates

Next-generation
Solid rocket booster (M-V FO)
Fig. by JAXA

Collaboration and support

- Supports from **LISA**
  - Technical advises from LISA/LPF experiences
  - Support Letter for DECIGO/DPF
  - LISA-DECIGO workshop (2008.11)

- Collab. with **Stanford univ. group**
  - **Drag-free control** of DECIGO/DPF
  - UV LED Charge Management System for DPF

- Collab. with **JAXA navigation-control section**
  - → formation flight of DECIGO, DPF drag-free control

- Research Center for the Early Universe **(RESCEU)**, Univ. of Tokyo
  - Support DECIGO as ones of main projects (2009.4-)

- Collab. with **UNISEC** (University Space Engineering Consortium)
  - Call for active young engineers

1. DECIGO

GW observation and Science

Pre-conceptual Design

2. DECIGO Pathfinder

Overview and Design

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Summary

DECIGO :

Formation flight with 3 S/C
1000 km separation
Precise meas. by laser interferometer

Fruitful Sciences
- Very beginning of the Universe
- Dark energy, Galaxy formation

DECIGO Pathfinder

Important milestone for DECIGO
Strong candidate of JAXA's satellite series

SWIM – under operation in orbit
first precursor to space!

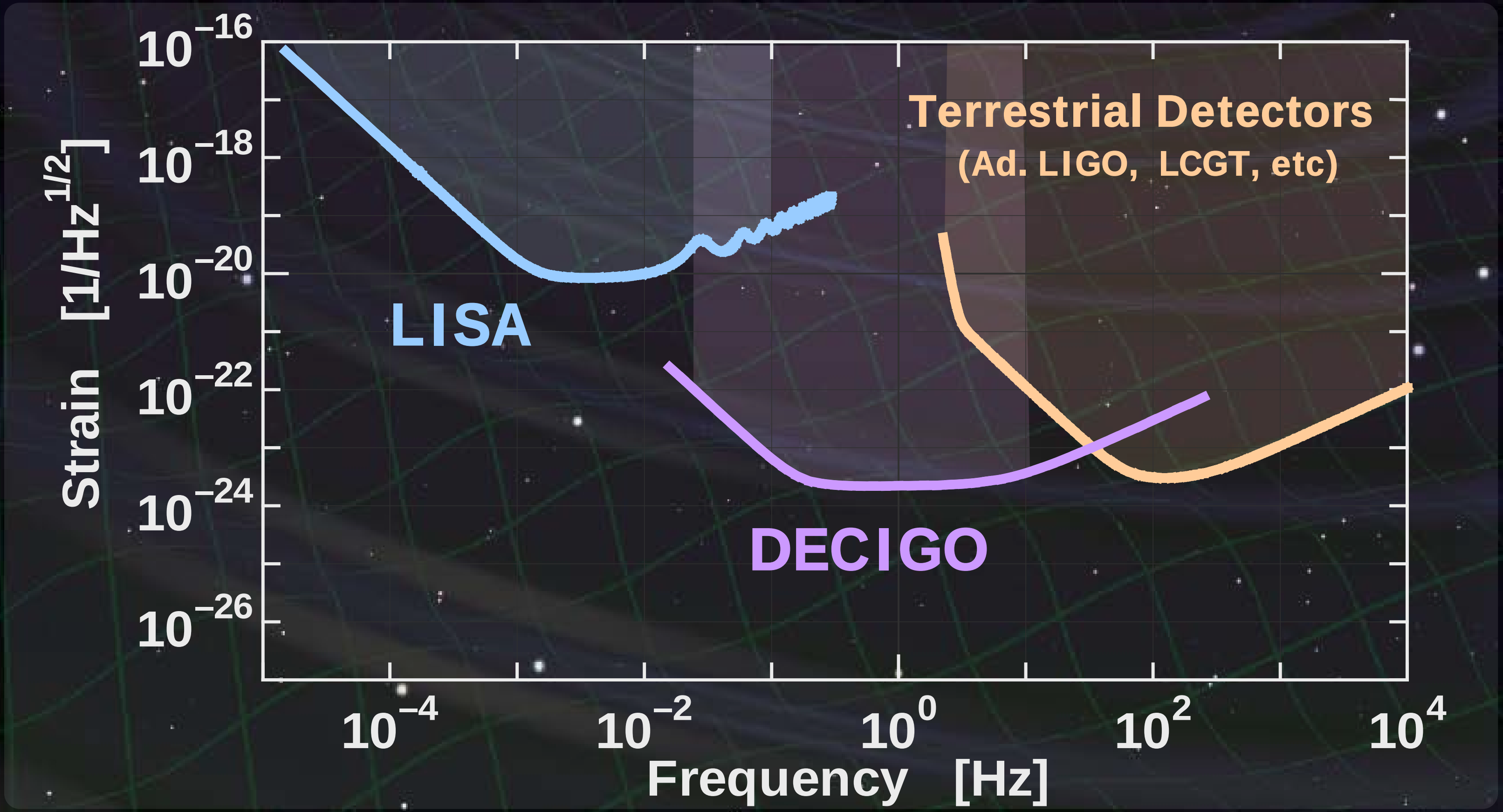
End

DECIGO

DECIGO (Deci-hertz interferometer Gravitational wave Observatory)

Space GW antenna (~2024)
Obs. band around 0.1 Hz

⇨ 'Bridge' the obs.gap between **LISA** and **Terrestrial detectors**



GW target of DPF

Blackholes events in our galaxy

IMBH inspiral and merger

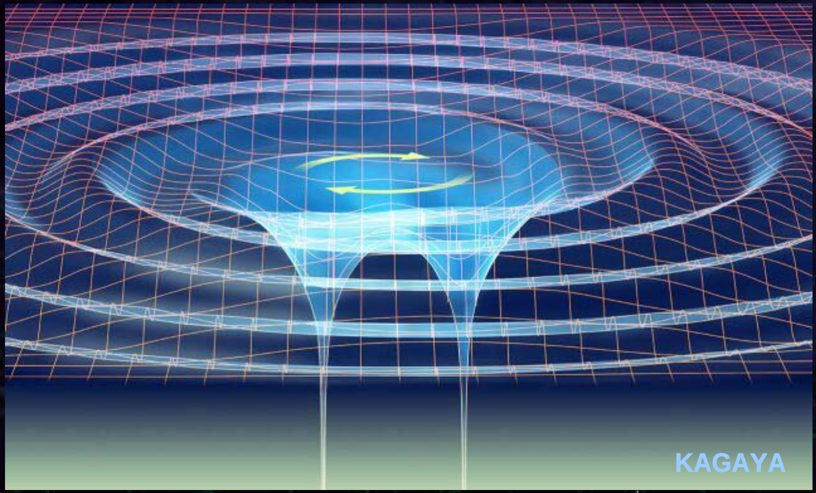
$h \sim 10^{-15}$, $f \sim$ 4 Hz
Distance 10kpc, $m = 10^3 M_{sun}$
Obs. Duration (~1000sec)

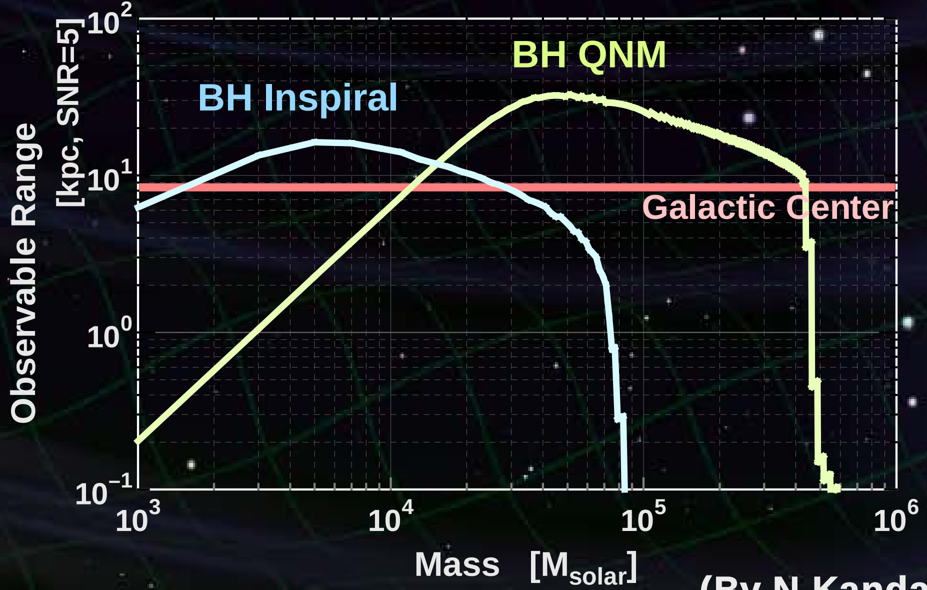
BH QNM

$h \sim 10^{-15}$, $f \sim$ 0.3 Hz
Distance 1Mpc, $m = 10^5 M_{sun}$

Observable range reaches the Galactic center (SNR~5)

Hard to access by others → Original observation

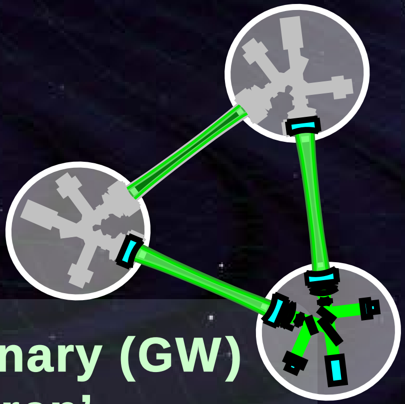




(By N.Kanda)

Standard Sources

Fig. from SNAP web page

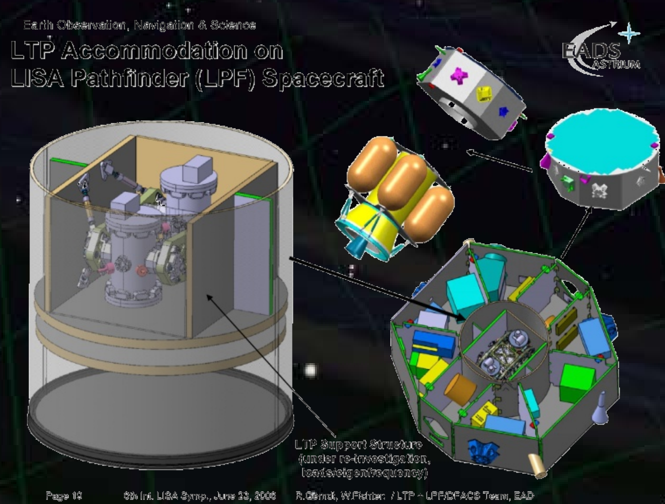


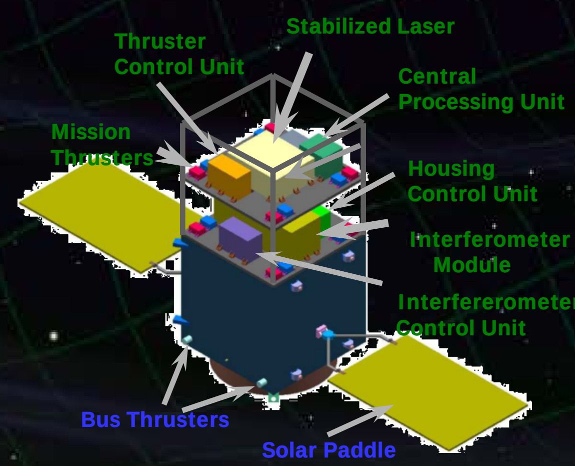
	Supernova (EM wave) 'Standard Candle'		Neutron-star binary (GW) 'Standard Siren'
Absolute power or amplitude	Extrapolated from nearby events	<	General Relativity
Event rate	2000 / yr (SNAP)	<	$10^{4\text{-}5}$ / yr (DECIGO)
Error in distance	~10 %	≈	10 % at z=1
Identification of host galaxy	Easy?	>	Require multiple detectors or statistics
Others	Uncertainty by dust absorption	<	Negligible interaction with matters

R.Takahashi (2006)

Comparison with LPF

	LPF (LISA Pathfinder)	DPF (DECIGO Pathfinder)
Purpose	Demonstration for LISA	Demonstration for DECIGO
		GW observation
Launch	2010	~2013
	Dedicated launcher (Vega)	Dedicated launcher (M-V follow-on)
Weight	1,900 kg	350 kg
Orbit	Halo orbit around L1	SSO altitude 500km
	Drag-free attitude control	Drag-free attitude control
Test Mass	Au-Pt alloy x2	TBD x2
Laser source	Nd:YAG (1064nm)	Yb:YAG (1030nm)
Interferometer	Mach-Zehnder	Fabry-Perot
Sensitivity	3×10^{-14} m/s^2/Hz$^{1/2}$ (1mHz)	1×10^{-15} m/s^2/Hz$^{1/2}$ (0.1Hz)





LCGT and DECIGO

LCGT (~2014)

Terrestrial Detector

→ High frequency events

Target: GW detection

DECIGO (~2024)

Space observatory

→ Low frequency sources

Target: GW astronomy

R&D for DPF (1)

Stabilized Laser

- BBM development
  - Yb:YAG (NPRO) source
  - Saturated absorption by I_2
  - → Stability test, Packaging

By M.Musha

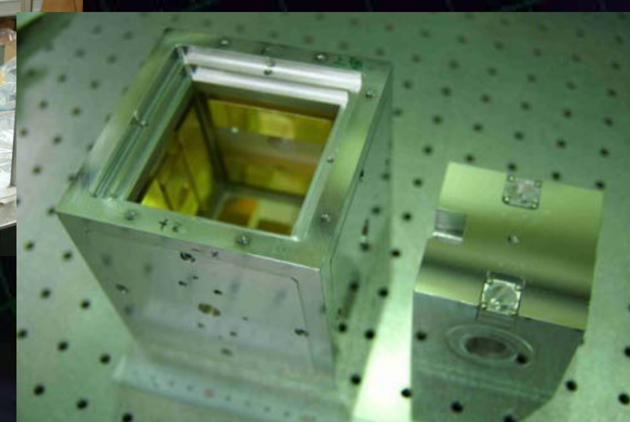
IFO and housing

- BBM-EM development
  - → Test of concepts
  - + Earth gravity sensors

S.Sato's talk
(P. Session #2, Today)
Y.Wakabayashi's poster

By A.Araya

By S.Sato



SWIM launch

Test of signal processing and control system

SWIM (Space-wire Demonstration module) **on SDS-1 satellite**

Launched in Jan. 23, 2009

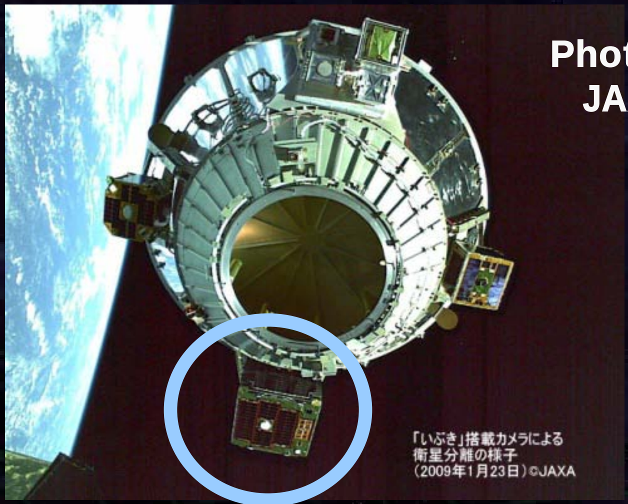


Photo: JAXA

SpaceCube2: Space-qualified Computer

CPU: HR5000
(64bit, 33MHz)
System Memory:
2MB Flash Memory
4MB Burst SRAM
4MB Asynch. SRAM
Data Recorder:
1GB SDRAM
1GB Flash Memory
SpW: 3ch

Size: 71 x 221 x 171
Weight: 1.9 kg
Power: 7W

Photo by JAXA

SWIMμν : User Module

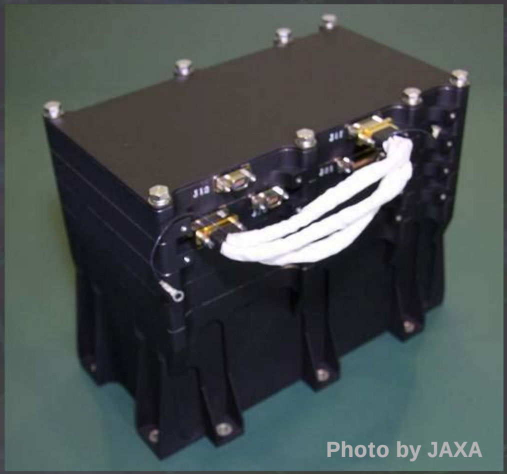
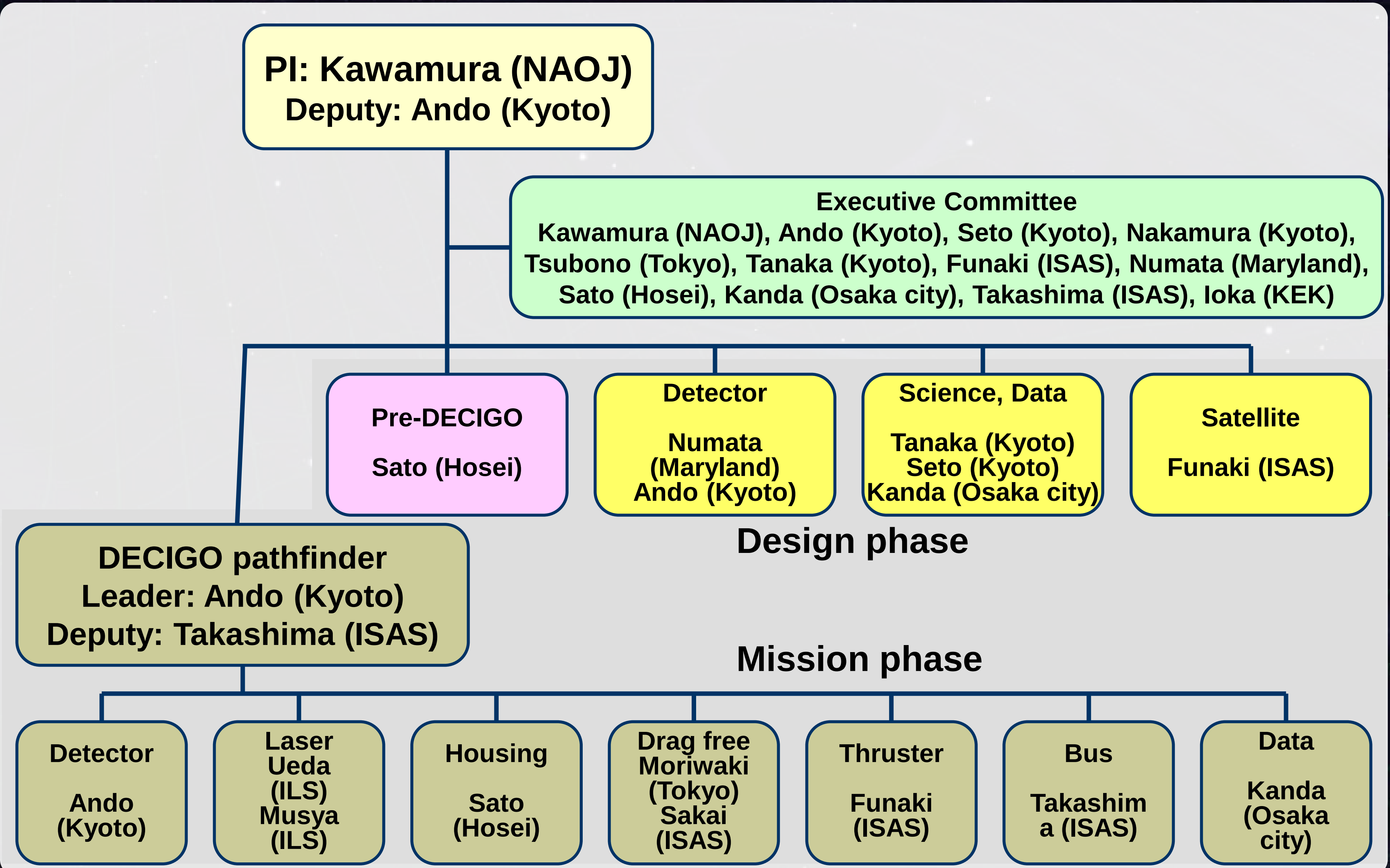


Photo by JAXA

Processor test board
GW+Acc. sensor
FPGA board
DAC 16bit x 8 ch
ADC 16bit x 4 ch
→ 32 ch by MPX
Torsion Antenna x2
~47g test mass

Data Rate : 380kbps
Size: 124 x 224 x 174
Weight: 3.5 kg
Power: ~7W

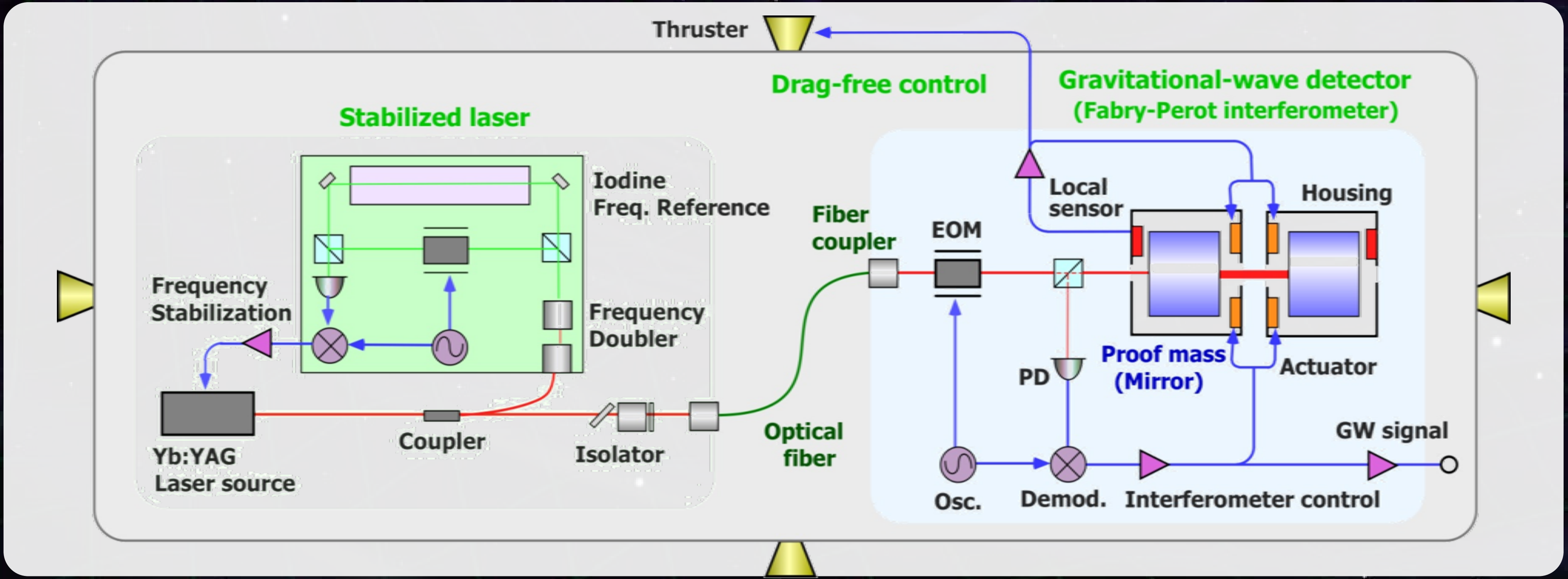
Organization



DPF mission payload

Mission weight : ~150kg
Mission space : ~90 x 90 x 90 cm

Drag-free control
Local sensor signal
→ Feedback to thrusters



Laser source
- Yb:YAG laser (1030nm)
- Power : 25mW
- Freq. stab. by Iodine abs. line

Fabry-Perot interferometer
- Finesse : 100
- Length : 30cm
- Test mass : 1kg
- Signal extraction by PDH

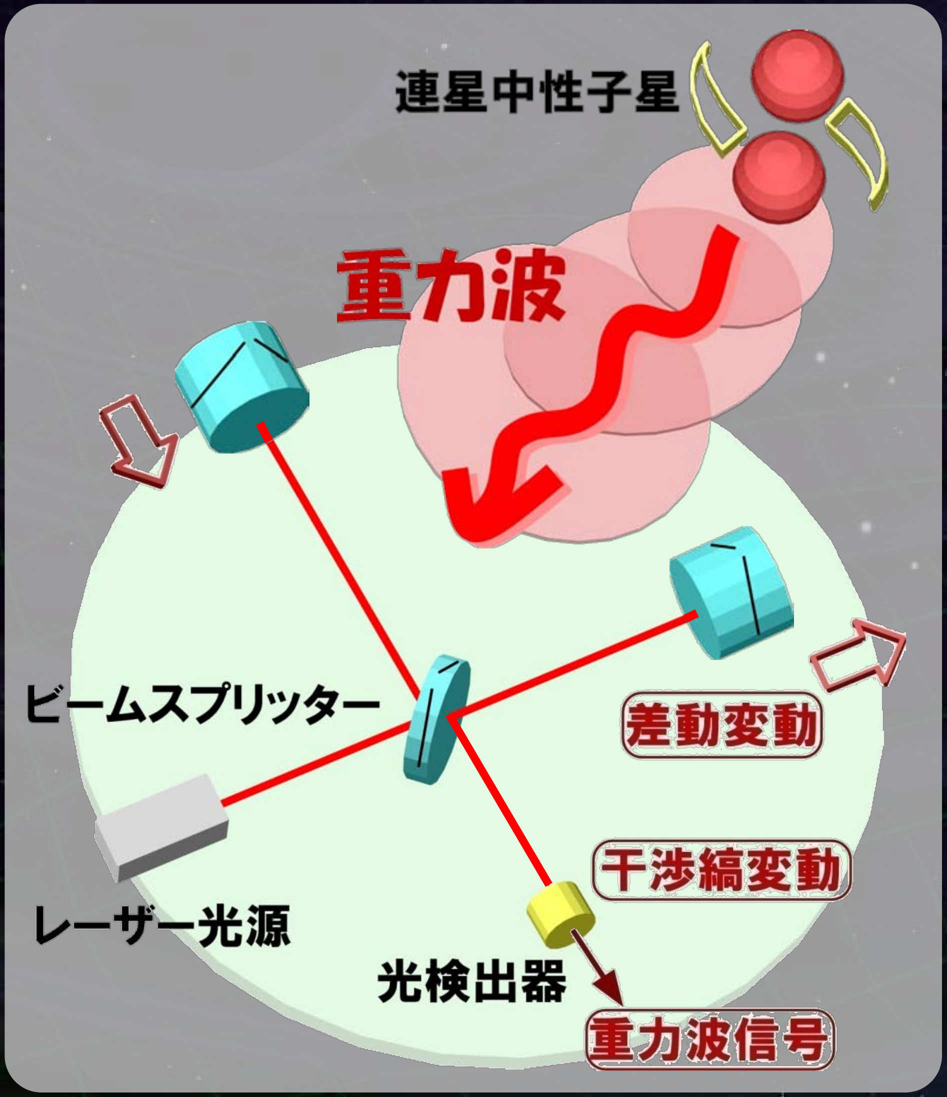
レーザー干渉計型重力波検出器

基本：マイケルソン干渉計
レーザー光源からの光を
直交する2方向に分岐

それぞれ、鏡で打ち返し干渉させる
干渉光を光検出器で観測する

重力波が入射

腕の長さの差動変動を
干渉光量の変動として検出



Introduction (3)

- **Expected science by GW observation**

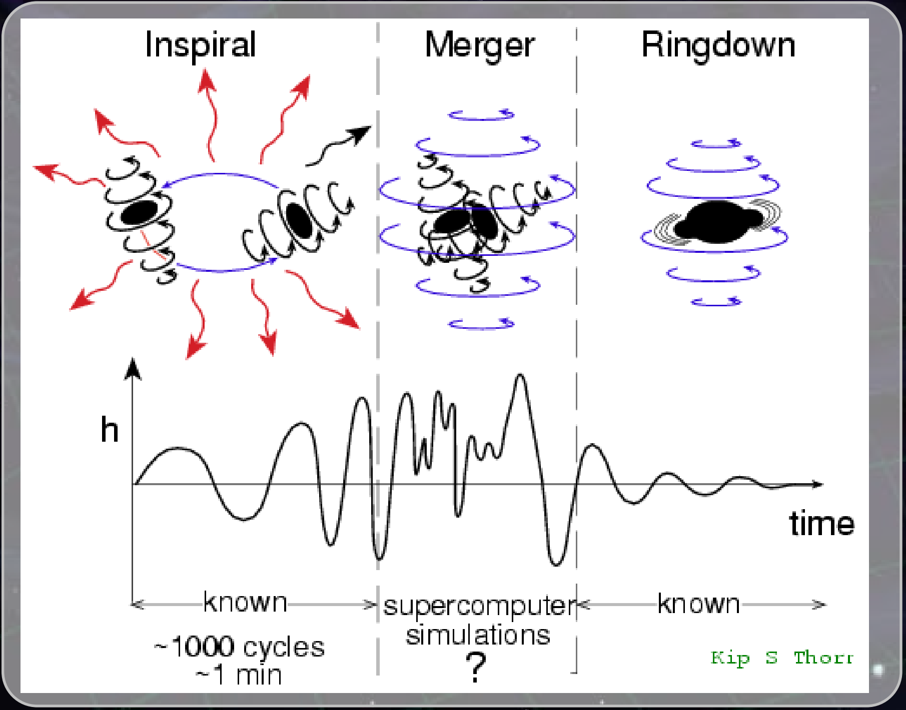
(ex.) Inspiral of binary neutron stars

Stationary orbital motion of 2 neutron stars
→ Stationary GWs
(Continuous wave)

Loose orbital energy by GW rad.
→ Higher freq. and larger GWs
(Chirp wave)

Collision and merger
→ Short GW radiation
(Burst wave)

BH quasi-normal mode oscillation
→ Decay of oscillation
(Ringdown wave)



⇒ **BH and NS physics**
Test of GR

Introduction (4)

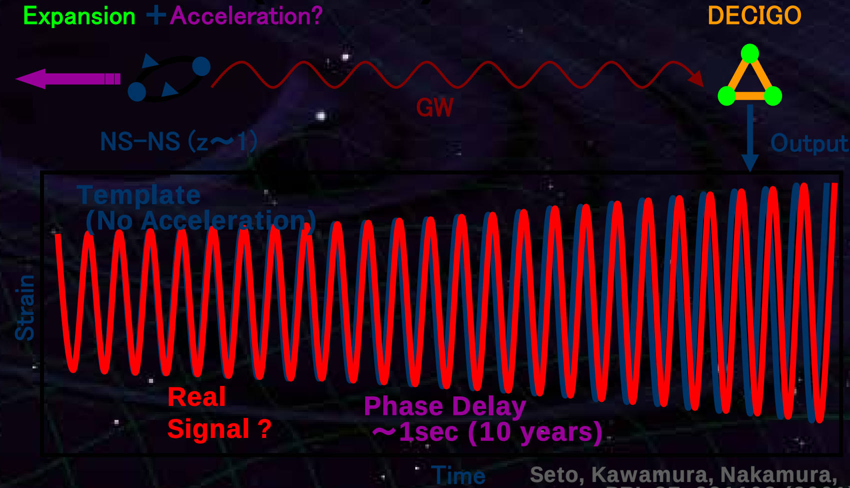
Expected science by GW observation (contd.)

Merger of intermediate-mass BHs
→ Formation of super-massive BHs
Galaxy formation

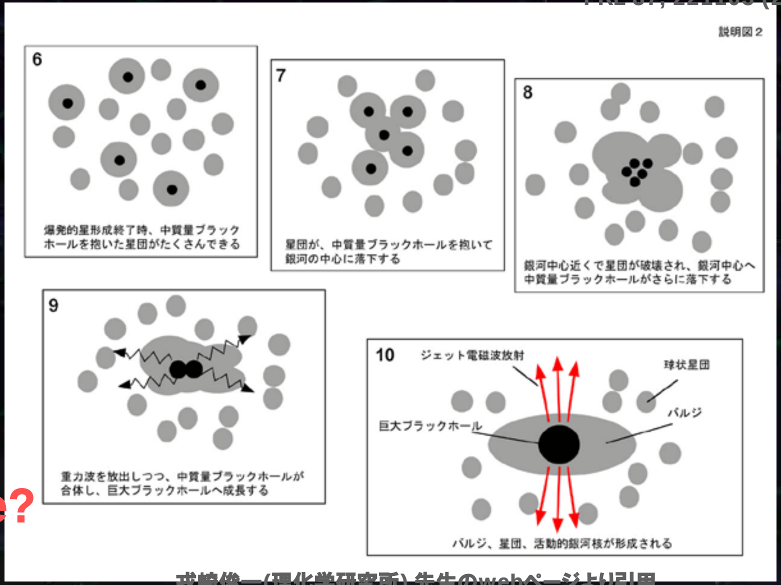
Distant neutron-star binaries
→ Direct measurement of acceleration of expansion of the universe
Information on dark energy

GWs from early universe
→ Insight on inflation

Unexpected GW sources
→ Paradigm change on the universe?



Seto, Kawamura, Nakamura, PRL 87, 221103 (2001)



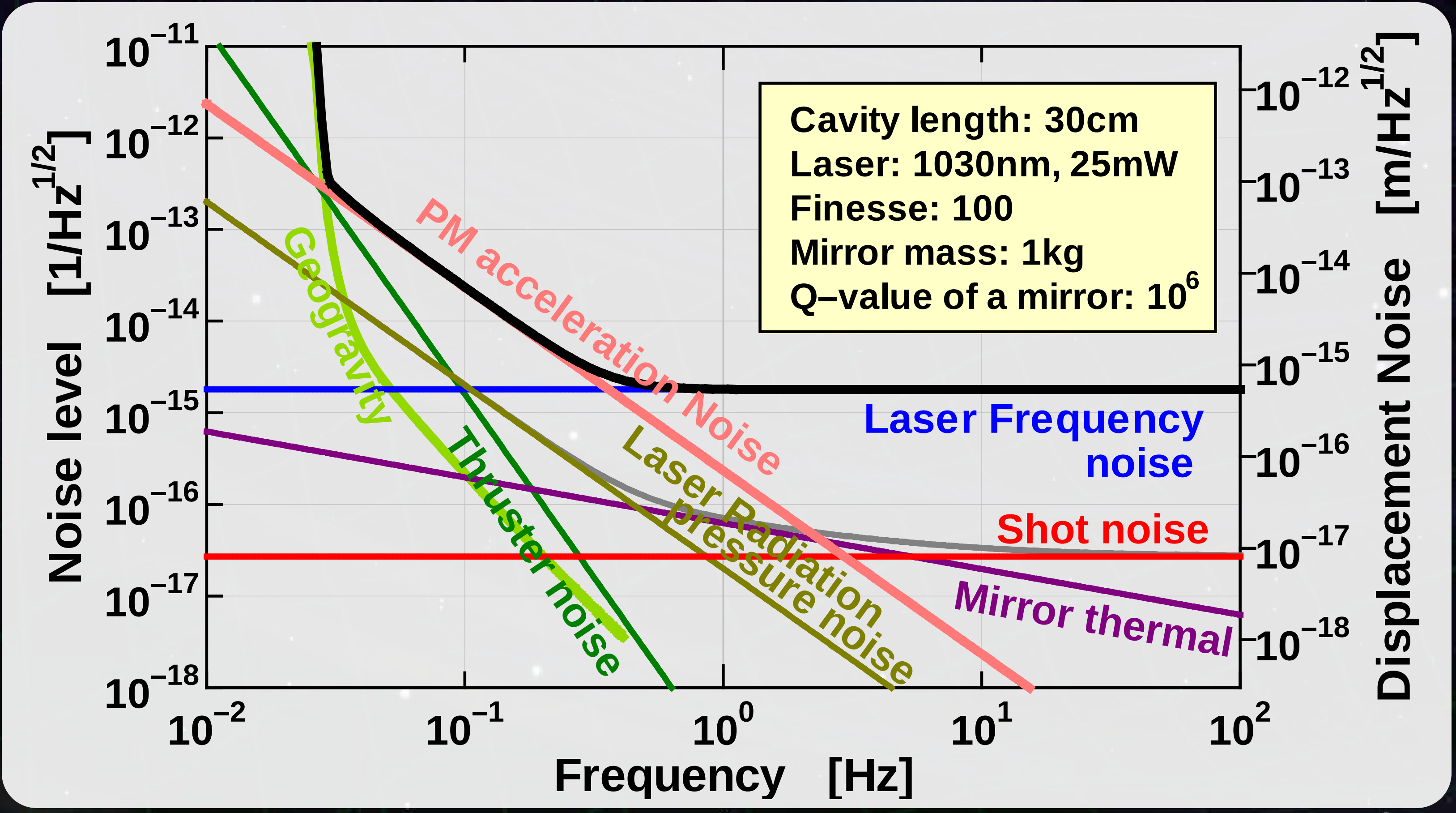
戎崎俊一(理化学研究所) 先生のwebページより引用
http://atlas.riken.go.jp/~ebisu/smbh.html

DPF Sensitivity

Laser source : 1030nm, 25mW
IFO length : 30cm
Finesse : 100, Mirror mass : 1kg
Q-factor : 10^5, Substrate: TBD
Temperature : 293K

Satellite mass : 350kg, Area: $2m^2$
Altitude: 500km
Thruster noise: $0.1\mu N/Hz^{1/2}$

(Preliminary parameters)

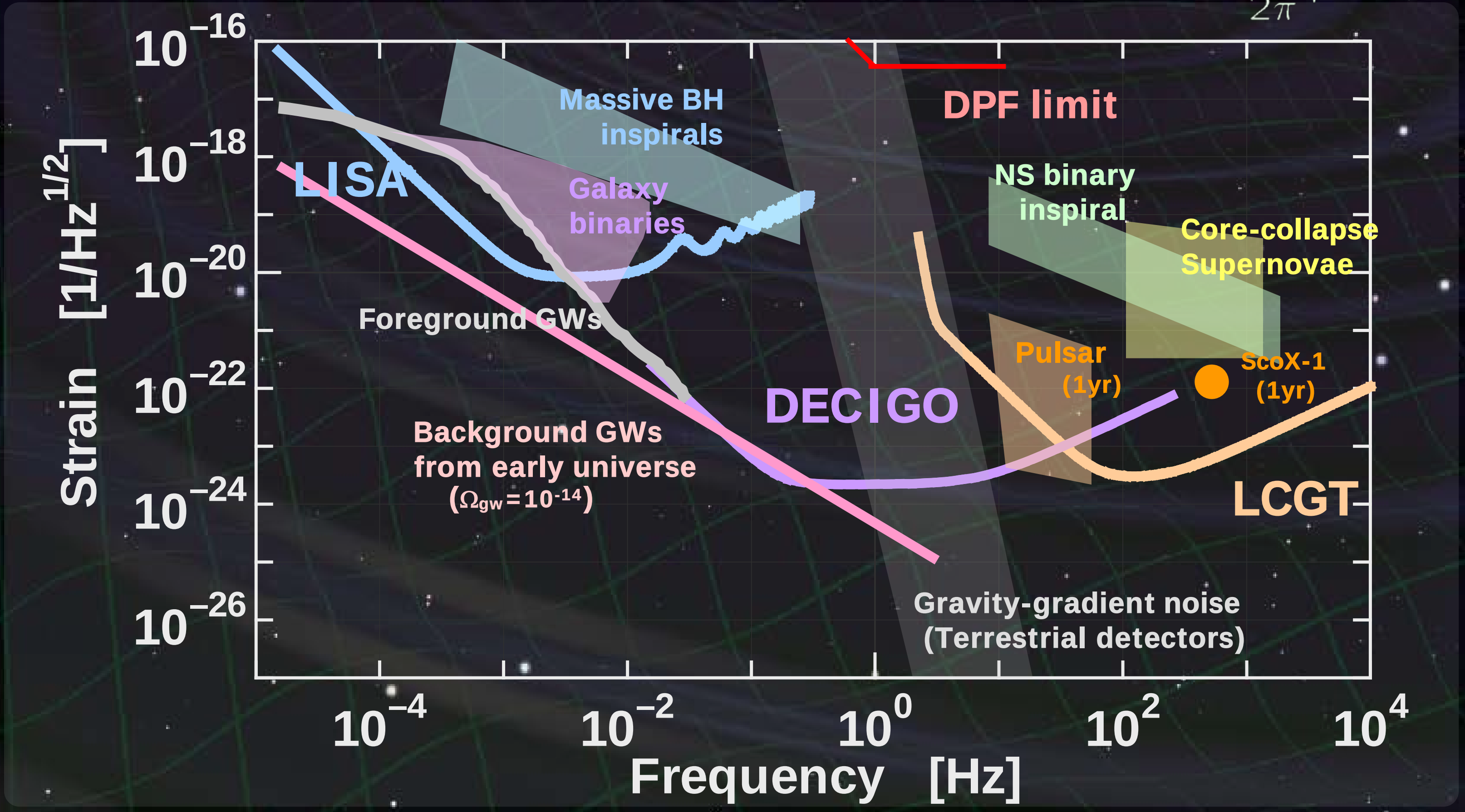


DPF sensitivity

DPF sensitivity $h \sim 2 \times 10^{-15}\ \mathrm{Hz}^{1/2}$

(x10 of quantum noises)

$$f \sim \frac{1}{2\pi}\sqrt{GM/R^3}$$

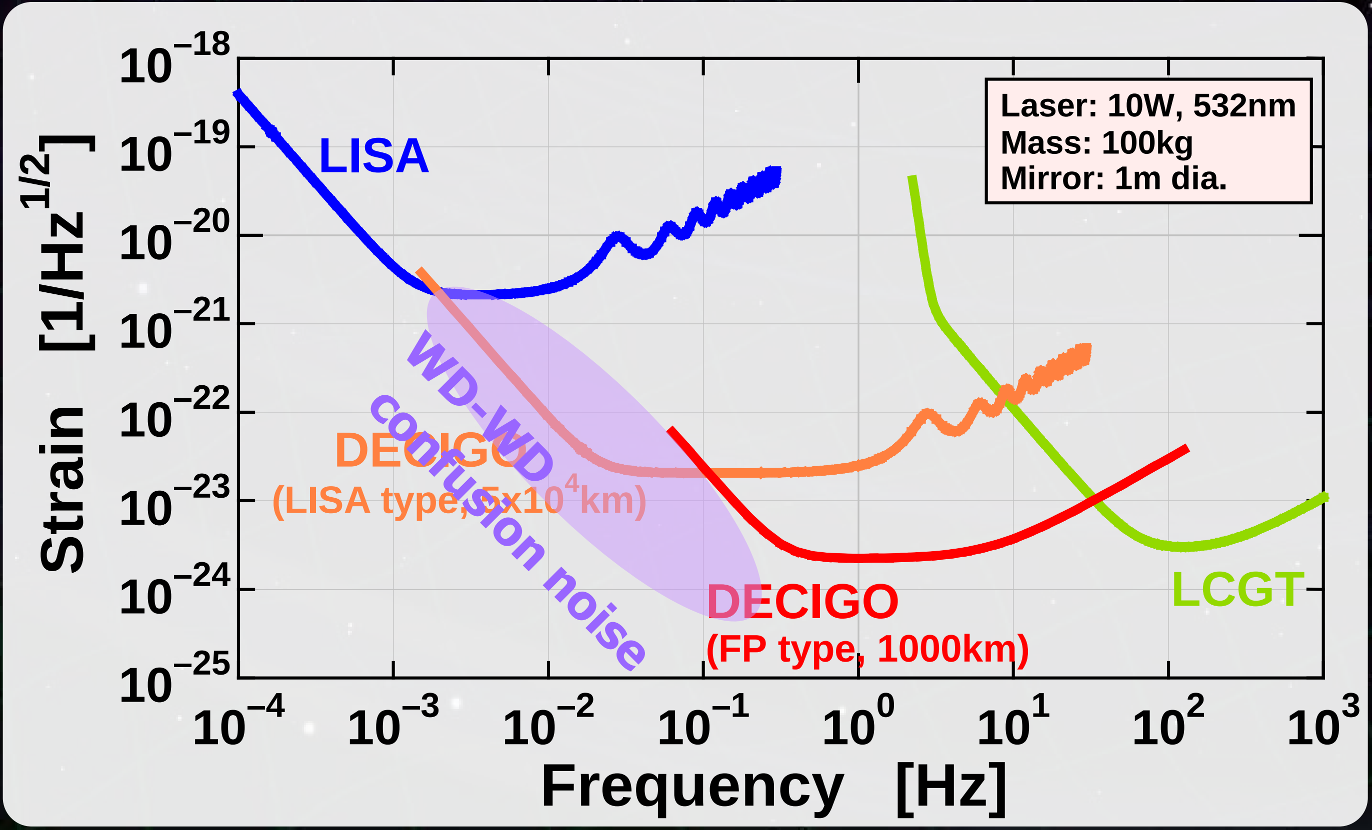


Interferometer Design

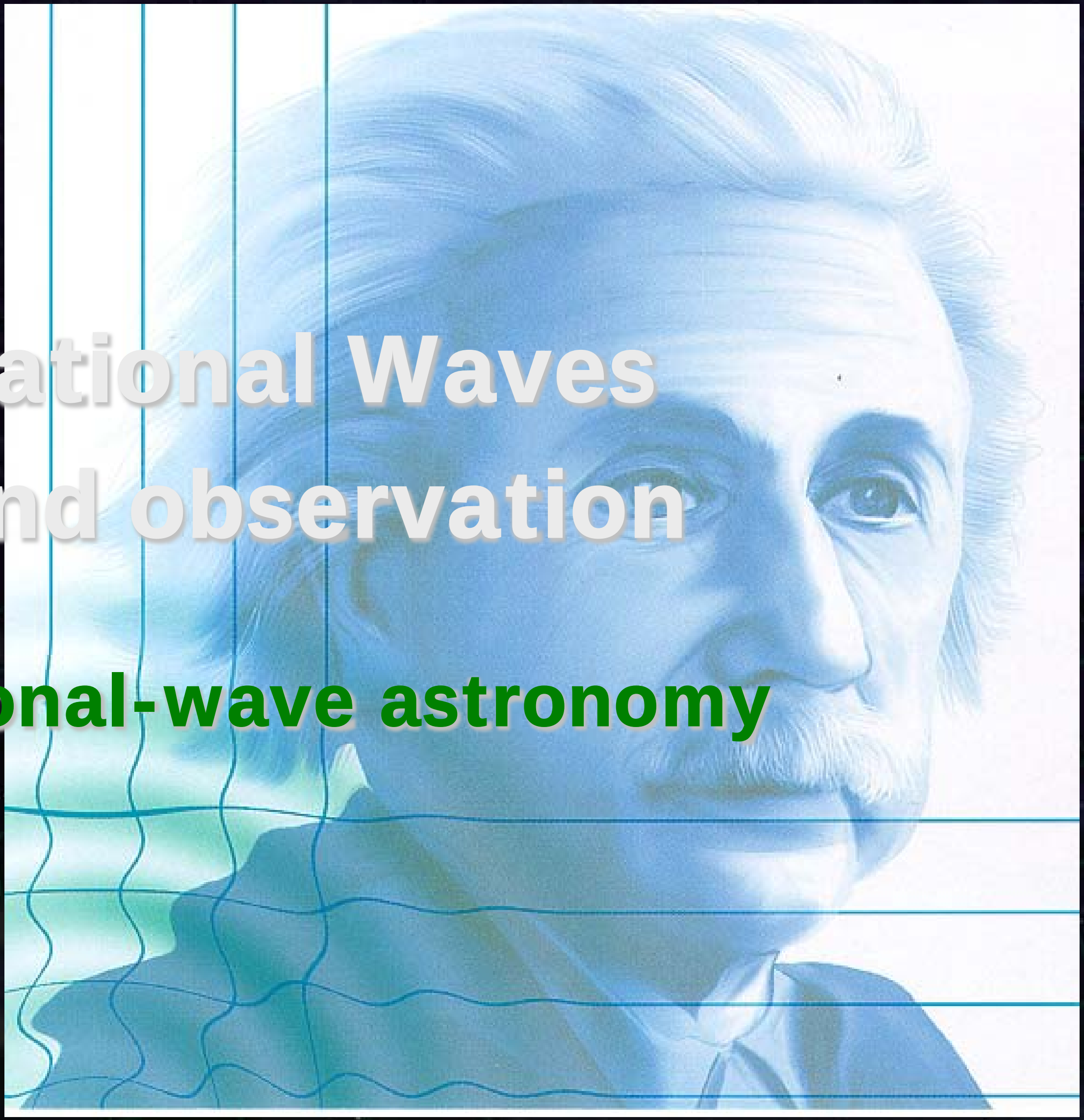
Transponder type vs **Direct-reflection type**

Compare : Sensitivity curves and Expected Sciences

⇨ **Decisive factor: Binary confusion noise**



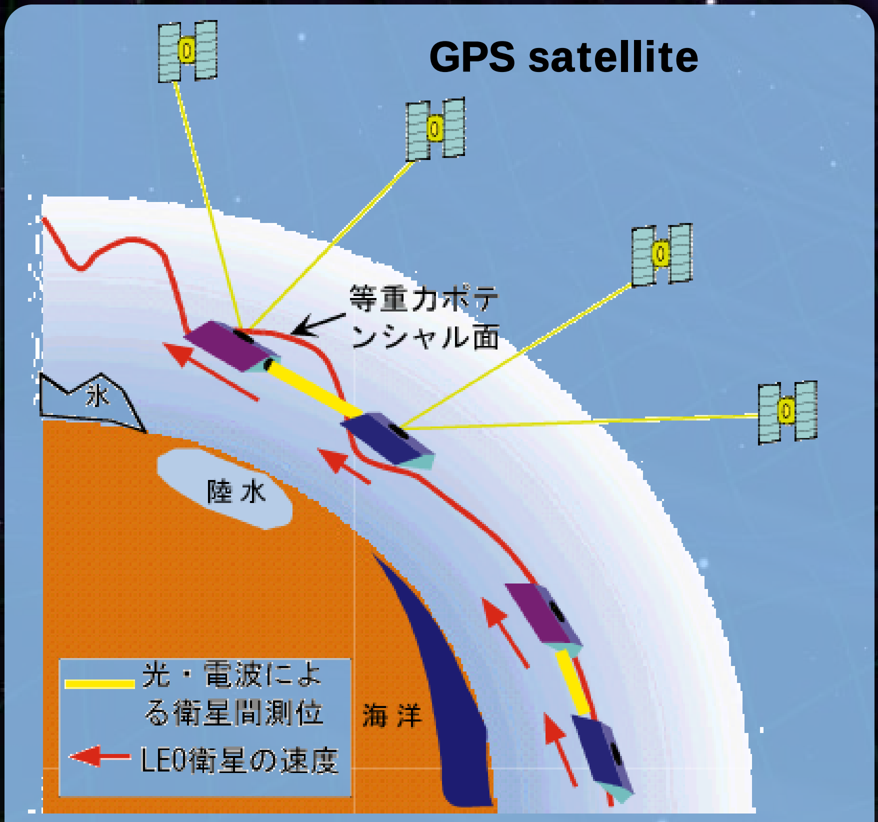
1. Gravitational Waves and observation



Gravitational-wave astronomy

Gravity of the Earth

Measure gravity field of the Earth for Satellite Orbits



東京大宇地震研·新谷氏、
京都大学·福田氏の資料 / 情報提供

Determine global gravity field
→ Density distribution

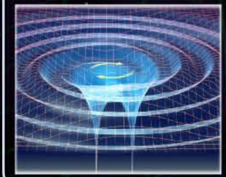
Monitor of change in time
Ground water motion
Strains in crusts by
earthquakes and volcanoes

Observation Gap
between GRACE and GRACE-FO
(2012-16)
→ DPF contribution
in international network

Objectives of DPF

Observation

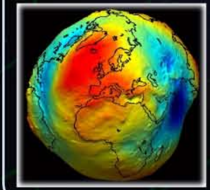
Gravitational wave



Intemedate-mass

inspiral and merger

Earth gravity



Environ. monitor

Geoid resolution

~1mm.

Science Technology

Space interferometer

Precise meas. in space

6×10^{-16} m/Hz$^{1/2}$

Stabilized laser

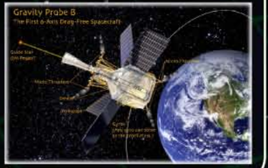
High stability in Space

0.5 Hz/Hz$^{1/2}$

Drag-free control

Low-noise control

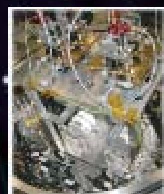
with passive stab.



DPF and DECIGO

DPF requirements

Precise meas. by IFO



Disp. noise
6×10^{-16} m/Hz$^{1/2}$

Force noise
10^{-14} N/Hz$^{1/2}$

4×10^{-18} m/Hz$^{1/2}$

10^{-17} N/Hz$^{1/2}$

Stab. Laser

Freq. Stability
0.5 Hz/Hz$^{1/2}$

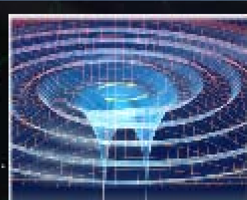
1 Hz/Hz$^{1/2}$

Drag-free control

Satellite disp.
10^{-9} m/Hz$^{1/2}$

Thruster noise
10^{-7} N/Hz$^{1/2}$

GW Obs.



0.1 Hz band
Observation and
Data analysis

DECIGO requirements

1000km FP cavity
- IFO control in space
- Low external force
- Large optics

Ultra stable Laser
- Stabilization of source
- Stabilization by long arm

Formation flight
- Stable orbit
- Inter S/C Ranging
- Drag-free control
- Low-noise thruster

Observation
- Data procession
- Data analysis
- Triggered search

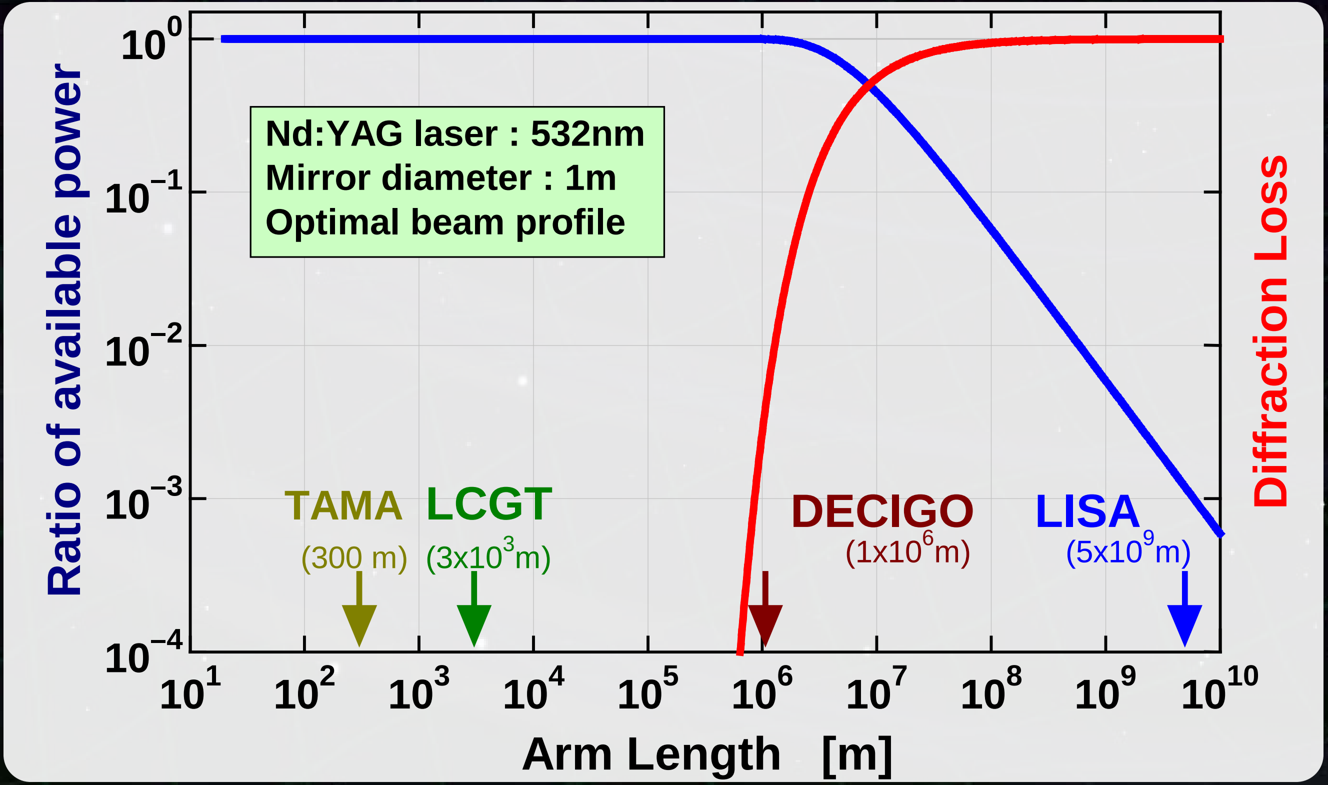
Arm length

Cavity arm length : Limited by diffraction loss

Effective reflectivity (TEM_{00} → TEM_{00})

- **Laser wavelength : 532nm**
- **Mirror diameter: 1m**
- **Optimal beam size**

⇒ **1000 km is almost max.**

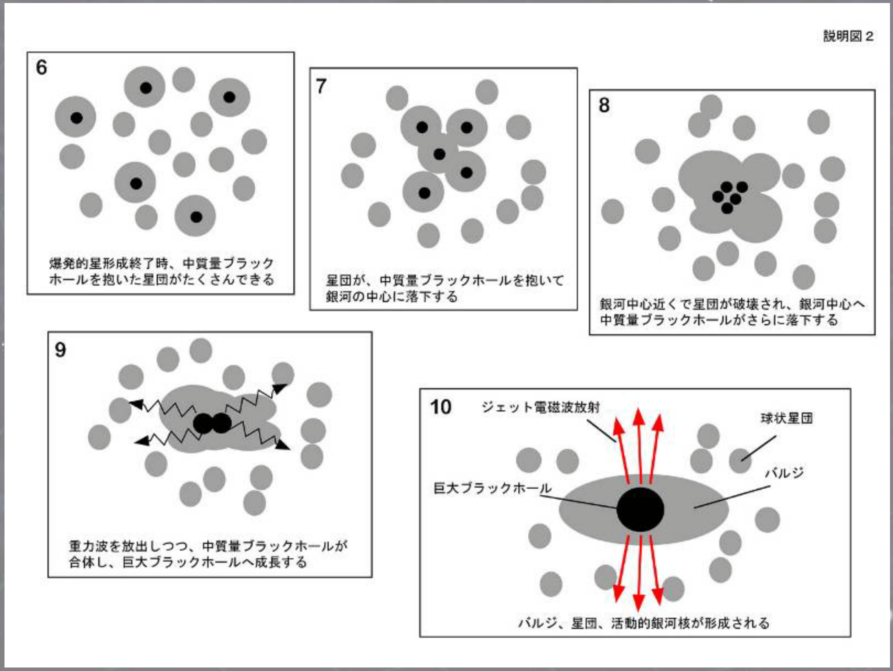


IMBH inspiral and Merger

DECIGO will observe
Intermediate-mass BH (IMBH)
binary merger with
SNR>6000 for z~1 source

⇩

Information on the
formation of
Supermassive BHs
at the center of galaxies



戎崎俊一(理化学研究所) 先生のwebページより引用
http://atlas.riken.go.jp/~ebisu/smbh.html

DPF targets

BHs in Globular clusters

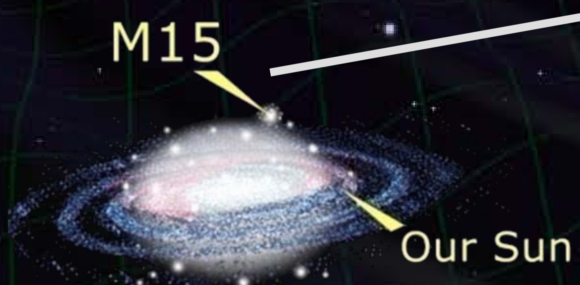
BH masses estimated from star motion

⇨ Estimate SNR of GW signals

Equal mass, Mass ratio 1:1/3, 100Msun BH capture

Credit: NASA, STScI

Globular clusters known to have black holes



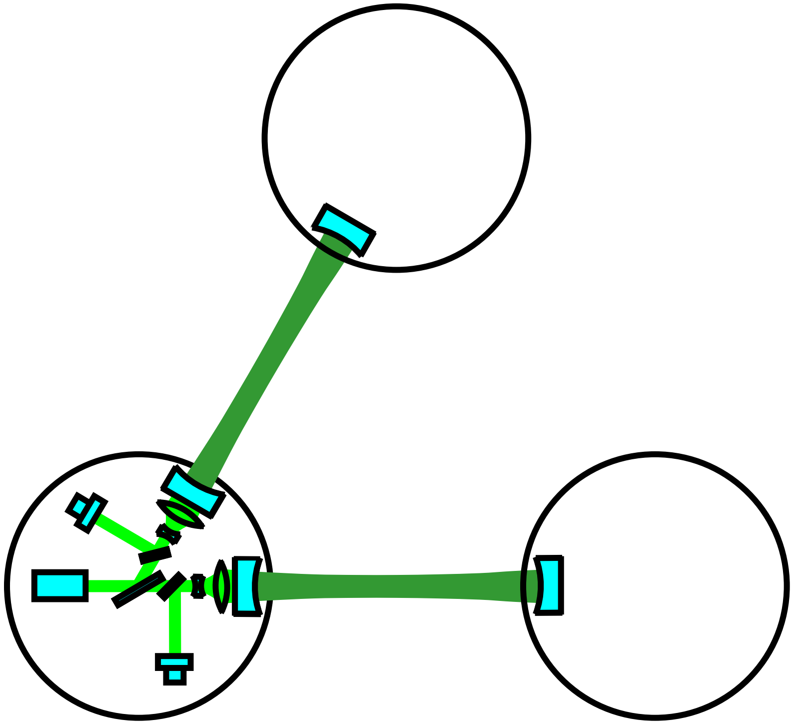
Milky Way Galaxy (artist's concept)

(~150 Globular Clusters in our Galaxy)

NGC#	BH質量 [Msun]	距離 [kpc]	SNR (同質量)	SNR (1:1/3)	SNR +100Msun	速度分散 [km/sec]
6441	12423.8	11.2	36.4	22.2	3.7	19.5
6256	4753.6	6.9	26.6	16.2	4.3	15.4
7078	4387.8	10.3	16.6	10.2	2.8	15.1
6093	3720.3	10.0	14.9	9.1	2.7	14.5
104	820.0	4.5	9.4	5.7	3.6	10
1851	1348.5	12.1	5.3	3.2	1.6	11.3
6681	820.0	9.0	4.7	2.9	1.8	10
6293	365.6	8.8	2.5	1.5	1.4	8.2
5286	443.8	11.0	2.3	1.4	1.2	8.6
6522	227.8	7.8	1.9	1.1	1.3	7.3
5904	142.0	7.5	1.3	0.8	1.1	6.5
6325	133.3	8.0	1.2	0.7	1.0	6.4
6752	45.0	4.0	0.9	0.6	1.3	4.9
7099	89.3	8.0	0.8	0.5	0.9	5.8
6284	170.7	15.3	0.7	0.5	0.6	6.8

(By N.Seto)

Pre-DECIGO



	Pre-DECIGO	DECIGO
Arm length	100 km	1000 km
Mirror diameter	30 cm	1 m
Laser wavelength	0.532 μm	0.532 μm
Finesse	30	10
Laser power	1 W	10 W
Mirror mass	30 kg	100 kg
# of interferometers in each cluster	1	3
# of clusters	1	4

SWIMμν

Tiny GW detector ~47g test masses inside
→ Levitated control in space

TAM: Torsion Antenna Module with free-falling test mass
(Size : 80mm cube, Weight : ~500g)

Test mass

~47g Aluminum, Surface polished
Small magnets for position control

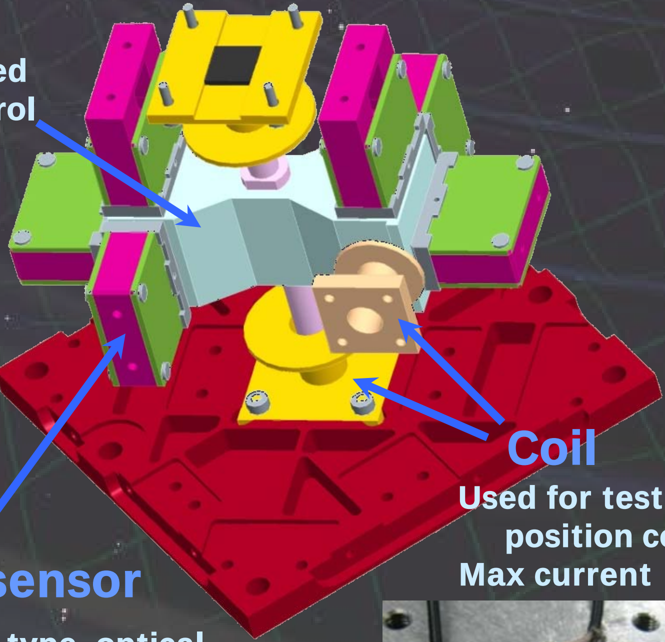


Photo sensor

Reflective-type optical displacement sensor
Separation to mass ~1mm
Sensitivity ~ 10^{-9} m/Hz$^{1/2}$
6 PSs to monitor mass motion

Coil

Used for test-mass position control
Max current ~100mA